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TRIPLE POINT DEVELOPMENT: TWO CASE STUDIES

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Abstract

Recent work has suggested that frontolytic strain may be a feature of a certain class of frontal wave instability. By considering one analysed case, it is suggested that this instability may manifest itself in the formation of triple point lows. Weak waves on the cold front of a frontal cyclone propagate on to the warm/occluded front at the triple point and develop significantly. When the warm front lies in frontogenetic strain, it is inevitable, from the geometry of the triple point, that the cold front will be in frontolytic strain. This process of triple point development seems to be relatively common over the Northeast Atlantic. Some of the implications of this model are discussed. It has been shown elsewhere that, at least in a barotropic instability model, frontolytic strain can yield very high growth rates of instabilities. Whether this is crucial to triple point development is not obvious, and it may be that the role of the cold front is simply to supply waves to the intense (frontogenetic) warm front.

In the second case considered here, the development at the triple point occurred through the same mechanism, and was associated with rapid propagation of the parent system. This process may be interpreted as being due to a transient Rossby wave behaviour.

1 Introduction

The idea of secondary cyclone development at the 'triple point', or 'point of occlusion', of a frontal cyclone (where, according to the Norwegian cyclone model, the cold front, warm front and occluded front meet) has been discussed for many years. The Bergen school associated the occlusion process intrinsically with the formation of a secondary low (Bjerknes and Solberg 1922).

Sawyer (1950) conducted a study of secondary developments of this kind in the period October 1947 to September 1948 and recorded 77 cases. Sawyer had specified distinct criteria for forecasting the formation of triple point lows in terms of the structure of the thermal wind field, which are illustrated by figure 1: good success was obtained when these criteria were used to forecast the 77 observed cases. These results of Sawyer's (1950) are still in current use in the UKMO Forecaster's Handbook and little further work seems to have been done on the subject until the 1990's—while Sawyer's work provides a good empirical guide to the forecasting of secondary development, it offers little physical insight into the mechanism of the development, without which the improvement of a forecaster's understanding of the process will be limited.

Sawyer's (1950) criteria for the forecasting of triple point development are notable, at least in the case of a cold occlusion, in requiring diffluence in the thermal wind field in this region. Recently, an objective study of ultra high frequency ($12 - 36hour$) atmospheric disturbances in the North Atlantic as seen in ECMWF analyses, undertaken by Ayrault *et al.* (1995) (ALJL), found two principal classes of frontal wave disturbance. ALJL were able to describe the development of the 'type 1' wave using established dynamical ideas, essentially instability of an intense cold front involving upper level precursors, but they argued that the 'type 2' wave requires some new dynamical explanations. In particular, the type 2 cyclone occured on a weak front, with a markedly *frontolytic* basic state, a configuration which for various reasons, discussed later, has received little attention in theoretical work, but which is perhaps reminiscent of the diffluent thermal wind pattern in Sawyer's (1950) model. It is proposed here that the type 2 cyclone found objectively by ALJL may be in certain cases a manifestation of the mechanism by which triple point lows form. These arguments lead to a dynamical model for triple point development. In simple terms, it seems that triple point lows form when a

frontal wave on the cold front propagates on to the warm front, where it is able to develop markedly.

2 Two examples

Two cases of triple point development, as observed in the UK Meteorological Office Limited Area Model output (UKMO LAM output) will be described here. The first, which occurred on 14 November 1992, is a case which featured as a 'type 2' development in ALJL's objective study using ECMWF analyses, and served as a motivation for the work described here. The second example, from 17 February 1996, was one of several cases observed during the daily forecast meetings taking place in the pre-FASTEX exercise (15 January to 15 March 1996) in the JCMM at Reading. This latter case exhibits certain features which help to clarify issues raised by the 14 November 1992 example; the 14 November case, as one of a generic group found by ALJL, suggests some generality of the ideas discussed here. Unfortunately, the UKMO archive of detailed LAM data does not extend far enough back in time to contain any of the other type 2 cases picked up by ALJL's analysis.

14 November 1992

This is the case which was identified objectively by ALJL, at time 6Z, in ECMWF analyses, and it is reassuring that it features clearly in the UKMO analysis (seen at 12Z, when it is closer to the UK, in figure 2). The parent low was relatively stationary at around 18W, 54N, with an intense warm front extending to the SE. The surface flow to the SW of the warm front was diffluent—the LAM analysis confirms a strong strain ($1 - 2 \times 10^{-4} s^{-1}$) on the front. The cold front was relatively weak, as might be expected in the given 'frontolytic' flow pattern. In addition, a mid- and upper-level trough lay in the cold air to the NW of the cold front and was propagating round the parent low: this trough was manifest in the satellite imagery as a region of patchy convection.

At 00Z on 14 November the cold front wave was plotted at around 22W, 41N, and although there is little indication of a clear wave in the LAM dynamical fields, such as vorticity or pressure, the METEOSAT IR imagery shows the wave distinctly (figure 3). Observational coverage of this region of the Atlantic is not comprehensive and the model will naturally have

difficulty in resolving a weak feature, so the absence of a clear signal in the LAM fields does not mean that there was no dynamical signature to the wave at this stage. During the morning of 14 November, the wave propagated along the cold front until at around 06Z it began to interact with the upper level trough which was impinging on the cold front from the NW; a wave may be seen to have developed on the upper level trough (figure 4). At this stage there were significant anomalies in the cold front vorticity and wet bulb potential temperature (θ_w) pattern (figure 4) at $900mb$, which may be associated with the upper-level coupling. In addition, it seems that, at least in the model, there were several wavelike anomalies in the cold front vorticity which again highlights the difficulties in accurately identifying the wave in model fields at this stage. The θ_w wave was more distinct: figures 4(b) and 4(c) show how it propagated on to the triple point, and elongated in the strain flow to produce a banded structure, which seems to be reminiscent of the 'kinematic' wave growth described by Parker (1996).

Again, the situation seems to be clarified by reference to the satellite IR imagery: the wave can be seen to move distinctly on to the warm front at which time deep convection broke out, over Southern England (figure 3). Subsequently, the vorticity developed at the triple point, the parent low tracked southwards to the Bay of Biscay and filled, and the triple point low became dominant in the system (by 18Z on 15 November), remaining over Southern England (figure 5), and Southeast England experienced heavy rainfall, of around $10mm$, falling overnight. During the period from 12Z on the 14th, when the secondary appeared as a spreading of isobars on the warm front, to 12Z on the 15th, when it had begun to dominate the system, the pressure of the secondary only fell by around $5mb$.

The importance of the interplay between the cold front wave, the upper-level trough and the warm front is difficult to specify. The satellite imagery indicated a coherent wave propagating along the cold front to the triple point at which time it produced intense convection and a marked secondary development. However, the dynamical fields from the LAM show only small perturbations on the cold front prior to the interaction with the upper level trough and the subsequent propagation of an upper/lower level frontal wave, marked 'W' in figure 4, on to the triple point. Looking solely at the model analyses it might be said that this triple point low was merely a development of the kind discussed by Thorncroft and Hoskins (1990) in which an upper-level potential vorticity (PV) anomaly advected over the warm front to interact and

produce a warm front wave, independent of the role of the cold front. For instance, it could be argued that the development at the warm front was due to the northeastern tip of the upper trough overrunning the front in the region to the west of Ireland, in figure 4(a).

Due to having only sparse data coverage of the Atlantic region, it is more than likely that the LAM analyses could not exactly resolve the dynamical details of the cold front wave: this is a perennial problem in frontal wave study. Without idealised simulations (e.g. with and without the trough, with and without the wave), the question of whether the cold front wave or the upper level trough casued the triple point development is not perfectly resolved in this case. However, the coherency of the wave as seen by the satellite and noted by the forecaster (figure 2) suggests that its presence was crucial in the development: it would be a singular event if the upper level trough triggered a warm front development exactly at the same time as the cold front wave arrived. Instead, a reasonable explanation would be to say that a relatively weak cold frontal wave was intensified by coupling with an upper level trough (as is indicated by the LAM fields of figure 4(a)) and then, on impinging on the triple point, the coupled wave caused an intense secondary development: as such, this presents a causal mechanism for the development of triple point lows.

17 February 1996

A qualitative picture that arose through the pre-FASTEX exercise was the relatively common occurrence of the mechanism of triple point development described here. No objective analysis of the frequency of these events was made, but Sawyer's (1950) results show that triple point lows can often occur.

The case of 17 February 1996 was one of these examples of cold front waves impinging on the triple point, observed during pre-FASTEX. In this case, unlike the 14 November 1992 example, the development occurred over the Atlantic, so it precludes the possibility that the intensification was due to orographic triggering of convection. In addition, the cold front wave was well-established and more coherent in the dynamical fields than that of 14 November 1992, so the idea of the triple point low being simply an upper-level interaction with the warm front does not apply here. The feature which causes development is not an upper level trough being advected over the triple point, but a wave running up the cold front, with upper and lower features.

Both the parent low and the cold front secondary were formed on the intense thermal gradient off the East coast of North America. At 12Z on 16 February, the parent was off the southern tip of Greenland and the secondary just south of Newfoundland (figure 6). The secondary is clear in the dynamical fields: in this case, the secondary developed off the east coast of North America, where observational coverage is relatively good, and the feature was well resolved in the LAM analysis. It is worth stating that at this time, the secondary did not appear to be linked strongly to the evolution of the primary system, except in that it appeared on the primary's trailing cold front: the genesis of the secondary may be regarded as having been independent of the dynamics of the primary low. An upper level PV feature lay close to the northwest of the low level PV anomaly and the subsequent interaction produced a significant wave on the cold front of the primary system. This wave is visible as a coupled upper/lower level feature in the LAM fields for 06Z on 17 February, shown in figure 7. At this stage, although the upper level anomaly associated with the wave lies on the flank of the upper level trough (figure 7(a)), it is distinct from the main 'dry intrusion' of the primary system (figure 7(b)).

The secondary reached the triple point between 09Z and 12Z on 17 February, before which time the system showed little surface pressure signal (figure 8). Plotting the track of the low centre, as the local minimum of surface pressure (figure 9) shows that there was a 'jump' in the position of the low centre between 12Z and 18Z: this was a manifestation of the deepening to the east of the parent low, as the secondary met the triple point. Although this effect may have been enhanced by the effects of the orography of Iceland at 15Z (when the low centre split, between its 12Z location and a new centre to the southeast), the mean propagation between 12Z and 18Z was rapid compared with the speed of the low before and after this period. The rapid motion of the low appears to be a wave-like propagation of the feature: the secondary was able to 'feed' the low and to enable it to propagate. This is in apparent contrast with the case of 14 November 1992 where the secondary developed at the triple point while the primary filled. Here it seems that the secondary recharges the primary system on its eastern flank.

Plotting the low centre as the maximum of $900mb$ relative vorticity gives a more extreme 'jump' in the low position: using this diagnostic, the secondary low remains distinct from the primary, which persists as a local vorticity maximum to the west of Iceland but weakens,

perhaps reminisent of the 14 November 1992 case.

In contrast to the 14 November 1992 case, in which there may be ambiguity as to the role of upper level forcing, this second example is of a developed secondary system interacting with the triple point. As such it strengthens the argument that development at the triple point occurs by the interaction with a cold front wave, rather than with an upper level trigger or a local 'instability', perhaps due to orographic forcing of convection. This example also gives another indication of the possible consequences of the triple point development: while in the 14 November 1992 case the secondary development coincided with the decay of the parent system, the 17 February 1996 case shows the primary cyclone being fed by the secondary, and experiencing a rapid propagation as a result of the development.

Understanding of the detailed dynamical processes involved in these interactions will require the development of dynamical models. Some further insight into triple point behaviour may be gained from considering baroclinic lifecycle experiments, which may be said to be good testbeds for dynamical ideas in midlatitude cyclones, and some of these are discussed next.

3 Triple point lows in baroclinic lifecycle simulations

In recent years, with the advent of increasing computer power, various authors have used numerical models to perform nonlinear 'baroclinic lifecycle experiments', in which the instability of a planetary scale midlatitude baroclinic zone is followed through the evolution of a baroclinic wave. Dry simulations of this kind have successfully reproduced many of the mechanisms and features of observed frontal cyclones (e.g. Thorncroft, Hoskins and McIntyre, 1993) and, in recent higher-resolution simulations, have been able to simulate secondary cyclone development on the more intense frontal zones which develop within the baroclinic wave. Thorncroft and Hoskins (1990) showed how an upper level feature was able to trigger development on the low level PV strip at the cold front of such a baroclinic wave, and demonstrated that, in this case, the upper level interaction was necessary to trigger the rapid growth. Unfortunately, these simulations were not carried to later times, so it is not possible from Thorncroft and Hoskins' (1990) work to judge whether the secondary cyclone would propagate on to the junction of the cold and warm fronts, and whether any interaction might be expected there.

Thorncroft and Hoskins (1990) did, however, note waves developing on the cold front in the triple point region and ascribed these waves to the 'upstream development' mechanism; that is, to propagation of energy by short, neutral waves at the lower boundary away from the active warm frontal region. These waves seem to resemble the wavelike features of figure 4(b) and 4(c), but the fact that the wave appears to be propagating towards the triple point in the 14 November 1992 case seems to preclude upstream development as a mechanism for its generation.

Polavarapu and Peltier's (1993) high resolution ($30km$ in the horizontal) simulations were carried to a sufficiently late state of evolution to see, in some cases, successive frontal waves develop. Polavarapu and Peltier (1993) make the point that the waves develop near the frontal 'cusp' (which may be seen to be the triple point) after 'seclusion' of warm air has occurred, the warm air and main low centre lying to the northwest of the cusp. They suggest that the cusp may indeed be a preferred location for development of secondary systems, such as those described by Sawyer (1950). Polavarapu and Peltier's (1993) waves involved a mixed barotropic/baroclinic energy conversion: in contrast to Thorncroft and Hoskins' (1990) example, these waves were shallow and not thought to involve upper-level forcing. It is interesting at this stage to note that of the two cases discussed above, that of 14 November 1992 involved a seclusion of warm air to the north, at $900mb$ (figure 4), but at this level the case of 17 February 1996 did not exhibit a warm seclusion.

Baroclinic lifecycle experiments have been a useful testbed for secondary development, in that they represent the most realistic basic state for development outside a NWP model. Unfortunately, a common difficulty with these simulations is that the diffusion required to keep them stable results in somewhat artificial PV development, even in dry simulations with no planetary vorticity gradient, which is difficult to link to physical genesis mechanisms: this PV is crucial to the secondary instability. Low level PV anomalies are generally observed to occur along fronts, but if in a model the generation mechanism is unphysical, the subsequent instability may not be dynamically realistic. More practically, simulations often tend to become unstable shortly after the frontal wave develops, meaning that its subsequent evolution onto, and interaction with the triple point can not be seen. All this being said, lifecycle simulations will be perhaps the best models on which ideas of secondary development may be tested, through providing

the most pertinent three dimensional basic state.

4 Dynamical issues

The analysed cases discussed above have presented a mechanism for triple point development, as the propagation of a cold front wave on to the warm front, but there are certain dynamical questions which naturally occur. This section will address some of the issues which have arisen.

Role of the deformation flow

ALJL stated that the type 2 cyclone develops in a strain flow which is clearly frontolytic, and the 14 November 1992 case studied in more detail here, confirms this. Ayrault (1995) shows a different case of type 2 development in frontolytic strain, where the parent cold front lies between a low to the north and a high to the south: here the secondary develops as it emerges from between the cyclone and anticyclone, as discussed by Parker (1996). This configuration seems, qualitatively, to describe the environment of the IOP3 case of the FRONTS 92 experiment (Hewson 1993, Browning *et al.* 1995), which was observed in detail. Thus, not all type 2 systems are triple point developments, and triple point developments may not all involve frontolytic strain. With this in mind, it is natural to ask what effect, if any, the frontolytic flow has on the development.

To some extent the frontolytic basic state is a singular one for the parent front. Firstly, a frontolytic state by its very definition is not one in which intense, unstable fronts are likely to form. In addition, from a kinematic point of view, the orientation of the front relative to the frontolytic axis of the strain flow will tend to increase with time, as is illustated by the rotation of a two dimensional vortex strip relative to the strain axes (Dritschel *et al.* 1991). In other words, a front lying close to the frontolytic axis of the strain flow might be seen as a very transient state, since the front will rotate towards the frontogenetic axis (figure 10(a)).

It is the geometry of the parent frontal cyclone which allows the possibility of a frontolytic state on the cold front, as observed by ALJL: the existence of the triple point means that any cyclone with a strong warm front in frontogenetic strain will almost inevitably have a weak cold front in frontolytic flow (figure 10(b)). The work of Bishop and Thorpe (1994a,b) (and Dritschel *et al.* (1991) for the barotropic case) has shown how a frontogenetic strain

flow, while generating an intense front with short horizontal lengthscales, and consequently potentially rapidly-growing instabilities, acts to suppress the nonlinear growth of waves. As a consequence, the warm front of systems such as that observed on 14 November 1992 has a great potential for instability but this instability is suppressed. The LAM analysis for that case indicated that the warm front's frontogenetic strain field decreased during the period when the development occurred at the triple point and it may have been this larger-scale influence that allowed the secondary to capitalise on a highly unstable warm front. Renfrew *et al.* (1996) have shown other cases where secondary development occured in a large scale strain which was decreasing with time.

The way in which the frontolytic flow on the cold front *increases* the growth of waves as they move in towards the warm front is the subject of current work. The basic mechanisms are illuminated by the simple two dimensional vortex strip instability in frontolytic strain as studied by Parker (1996). In this case, growth of waves (measured in terms of wave slope on the distorted edge of the vortex strip) occurs kinematically, through the deformation by the strain flow (as is suggested by the θ_w evolution at $900mb$ in figures 4(b) and 4(c)), and, more transiently, through the barotropic instability mechanism. Extremely high growth rates are indeed possible, but are only significantly greater than that of the pure kinematic growth for a finite period. If waves are shorter than the short wave cutoff for instability, they grow only by the kinematic mechanism, being made shorter and increasing in amplitude exponentially, with the width of the front itself. Measuring growth in terms of wave slope may not be the most pertinent guide to the instability of frontal waves in practice, as high wave slope may not necessarily imply a meteorologically significant system; this work is currently being extended to more physically realistic fronts.

In conclusion, it seems that the triple point region is a generic location for frontolytic strain, if the warm front is frontogenetic, and as such may be a generic region for type 2 development. In addition, theoretical work has shown that such frontolytic strain may give very rapid transient growth of secondary waves. However, it is not clear whether the strain is essential to the process of secondary waves interacting with the triple point itself—it might be argued that the strain contributes only by advecting the cyclones on to the warm front—and this question is only likely to be addressed by idealised studies.

The triple point

In this paper the development of waves at the triple point of an occluded frontal cyclone has been discussed. One reason why 'triple point development' has perhaps not received wide attention in recent years is the question of the observational and dynamical foundation of the triple point itself. The system of cold, warm and occluded fronts in the Norwegian cyclone is a simple model which perhaps may be seen as too simplistic when compared with observed systems. For instance, in the case of 14 November 1992, the cold front itself is weak and diffuse in the region of the 'triple point' and the LAM analysis shows little obvious distinction between the 'warm' and 'occluded' fronts as analysed by the UKMO forecaster (figure 2). Notably, the objective frontal analysis (figure 5; the method of computation of these fronts is described by Hewson 1996) shows the cold front failing to connect up with the triple point (practically, this means that it is too weak in this region to be captured by the objective method, as is to be expected for a front in a frontolytic flow) and plots the warm and occluded fronts as a single warm front. According to this objective analysis, it would be difficult and perhaps even misleading to locate a 'triple point', and the resulting secondary system might be better described as a 'warm front wave'. However, the term 'triple point low' is still a useful one, even if the triple point is not well defined, as it highlights the *mechanism* of the instability, requiring as it does a cold front and a warm/occluded front lying almost at right-angles to one another so that the cold front is able to generate the wave in its weakly frontogenetic (or even frontolytic) environment, and supply it to the warm/occluded front which may allow rapid instability.

In the 14 November 1992 case a better model for the frontal structure would be that of Shapiro and Keyser (1990) in which a warm front splits and forms a 'bent-back warm front' (figure 11). The bent back warm front model intrinsically exhibits the diffluent ('frontolytic') flow at the junction of the cold and the warm fronts which seems to be important for the development of these triple point lows. Whatever the specific nature of the fronts in the model of the parent cyclone, the basic configuration observed in the observations remains the same, of the cold front supplying waves which may deepen when they reach the warm front.

The fronts

The warm front is an important component in the development of the triple point lows.

The warm front seems to be a region of high potential for instability, as a narrow strip of high potential vorticity at low levels. The flow in this region is such that the cold front wave 'collides' with the front and interacts intrinsically with it, so that it is in a sense 'blocked' by the strain flow in this region. The cold front is a region which may supply finite amplitude waves, since there is no frontogenetic flow suppressing waves in this region, but since the cold front is weak these waves have little potential for growth until they reach the warm front. They propagate onto the warm front, are trapped and provide a finite amplitude trigger for instability.

In addition to allowing dynamical instability, the warm front is a region where there is likely to be low moist stability, and this may enable the cold front wave to initiate a rapid development of deep convection at the triple point. For instance, in the 17 February 1996 case, figure 7(b) shows a tongue of high potential vorticity at $500mb$ extending into the centre of the parent system, associated with a 'dry intrusion' in the satellite water vapour imagery. The overrunning of a warm front by such a dry intrusion might be expected to create potential instability in advance of the front, as described by Browning (1990).

Although the cold front may be a relatively weak feature, in its frontolytic environment, it seems to have an important role in this mechanism of development. Firstly, it serves as a nursery for the waves which may eventually produce development or propagation of the primary system, and secondly, it acts as a guide for the waves, since they propagate along the PV (or surface temperature) gradient which the cold front represents. This seems to be in contrast to certain systems approaching an 'omega block' which may be deflected to the north of the high pressure system, away from the axis of the deformation flow and lack a strong zonal front on which to move (as discussed below).

System development

It has already been noted that the influence of the secondary on the primary system differs in the two cases considered here. On 14 November 1992 the secondary developed while the primary filled, leaving the secondary as the significant centre in the system. On 17 February 1996, the secondary did not develop as a new cyclonic centre, but merged with the primary, to the extent that it caused an extension of the trough to the east and thereby induced a rapid propagation of the primary low centre.

The 17 February 1996 example resembles the mechanism of Rossby wave propagation.

Southerly advection of high potential temperature or high potential vorticity produces increased vorticity on the eastern flank of the low: this gives eastward propagation. In the 17 February case it seems to be a low level positive PV anomaly which is advected in to the triple point: this positive PV advection is contrary to the planetary PV gradient which would give negative PV advection in a southerly flow. Thus, the wave-like propagation resembles the diabatically forced wave of Parker and Thorpe (1995) where latent heating is the source for the low level PV on the eastern flank of the system, and this acts cooperatively with the planetary meridional temperature gradient which implies positive thermal advection here.

It is interesting that the wave-like propagation of the primary system occurs in a pulse, as the secondary arrives. This suggests that one may speculate a series of waves on the cold front causing a series of rapid jumps in the low position through this propagation mechanism.

Blocking

It has become relatively common for forecasters at the UKMO to plot a long, almost north-south oriented occluded front to the west of a blocking system over Western Europe, and this configuration is confirmed by the objective analyses, as, for example, in the case of 7 March 1996 (figure 12). As is known from observational and idealised studies (e.g. Haines and Marshall 1987), low pressure systems crossing the Atlantic tend to be diverted northwards by the flow around a blocking high and it is thought that these systems 'feed' the block and allow it to persist. The basic configuration of the flow to the west of the blocking pattern resembles that of the triple point of the frontal cyclone, in that there is a frontogenetic strain flow on the principal front (in this case the north-south oriented occlusion) and cyclones impinge on the front from the west, travelling along the 'frontolytic' axis of the strain flow. Such cyclones are in an environment reminiscent of that of the case shown by Ayrault (1995) which is emerging from between a low to the north and a high to the south, and as such may be expected to experience enhanced growth in the frontolytic strain flow. In the 7 March 1996 case there is not a clear cold front along the frontolytic strain axis, except for the relatively weak midlatitude temperature gradient, and it is possible to speculate on the dynamical differences between this situation and that of the waves on the cold front of a frontal cyclone. The lack of a distinct cold front may allow the impinging cyclones to be more easily deformed by the strain flow: this will have a bearing on the likelihood of breakdown of the block.

In a more basic sense, this scenario illustrates the overall effect of a general strain field on secondary instability. Frontogenesis occurs along the frontogenetic axis of the flow, but instabilities on this axis are suppressed. On the frontolytic axis, a front will be weak, and decaying with time, but the growth of instabilities is enhanced by the strain flow. Growing waves are advected on to the stationary point of the flow, where they meet a front which is intense, and therefore potentially unstable, but in a flow which now suppresses the incoming wave. The subsequent development will depend on whether the secondary disturbance is able to gain sufficient amplitude to influence the strain flow itself. In the 7 March 1996 case, the cyclone was diverted to the north, to merge with the primary cyclone near Greenland, while its vorticity pattern was deformed by the strain flow to lie along the frontogenetic axis and reinforce the 'occluded' front: in this case a development at the 'stationary point' did not occur.

5 Summary

The work of ALJL identified a new class of frontal wave instability, referred to as 'type 2', that is characterised by an environment of frontolytic strain. One form of this instability is exemplified by the example of Ayrault (1995), where a cold front wave emerges eastwards from between a low to the north and a high to the south: this example has been discussed by Parker (1996) and may also relate to certain blocking situations. However, the type 2 system which is considered here occurs as a wave on a cold front propagates on to the triple point of a frontal cyclone. The case of 14 November 1992 was an objectively analysed type 2 wave of this form, and occured in a cyclone for which the warm front was under frontogenetic strain: in this event, the frontolytic strain on the cold front was a result of the geometry of the triple point region.

It is proposed that this presents a mechanism for triple point development. Development on the warm front as cold front waves arrive seems to be common, but whether all such events experience frontolytic strain is not clear. It may be that rapidly growing type 2 waves appear in advance of a triple point development because the triple point is one region where frontolytic strain may be generic. If this is the case, two development mechanisms are being discussed in this paper; type 2 development and triple point development. However, Sawyer's (1950) work

suggests that a suitable strain field may be necessary for development at the triple point, in which case a type 2 situation is necessary for a triple point low, and the dynamics are bound up with the existence of frontolytic strain. It should be recalled that not all type 2 waves occur at a triple point, as Ayrault's (1995) example shows. Clearly there is a need for more dynamical understanding of these mechanisms.

The second case studied here has clarified some of the primary issues raised. In this case, it was more easily apparent that the wave causing the development was not merely an upper level feature but a developing cold front wave. In addition, the subsequent evolution in this case showed how the secondary wave's transport of positive PV into the eastern flank of the system caused a rapid Rossby wave propagation of the primary centre, in the opposite direction to that of a planetary Rossby wave.

In summary, it has been shown here that:

- Triple point lows develop when cold front waves interact with the warm front
- Some type 2 waves are/become triple point lows, since the triple point is a generic region for frontolytic strain on the cold front
- Triple point development can cause rapid, transient propagation of the primary system

The many outstanding questions raised by this study will require objective climatology studies, idealised dynamical models or better analyses if they are to be answered: some of this is currently being undertaken.

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Figure 1: The surface pressure and $1000 - 500mb$ thickness fields typically associated with development of a secondary low at the point of occlusion. (a) Warm occlusion; (b) cold occlusion, at which a diffluence of the thickness lines at the point of occlusion is required for development. In both cases, the arrow shows the subsequent movement of the secondary. From Sawyer (1950).

Figure 2: UKMO analysis for the UK at 12Z on 14 November 1992, as it appears in the Daily Weather Summary. The secondary cold front wave can be seen at about 8W 47N, propagating on to the point of occlusion.

Figure 3: METEOSAT IR imagery for 14 November 1992, at times 00Z, 06Z, 12Z and 15Z. At 00Z the incipient wave can be seen developing at around 30W, 35N. The warm front lies across the UK and is exhibiting some banded structure. The cold air trough is marked by a region of patchy convection around 25W, 48N. At 06Z the wave is more developed and by 12Z it begins to interact with the warm front. By 15Z very deep convection, with cloud tops colder than $-50°C$, has developed over England and Wales, and a separation of the isobars on the warm front at this time indicates the wave development.

Figure 4: UKMO LAM analyses for 14 November 1992, showing: (a) vertical component of absolute vorticity at $900mb$, shaded and narrow contours ($/10^{-5}s^{-1}$; contoured every $2 \times 10^{-5}s^{-1}$) superposed with the upper level PV height field (heavy contours; contoured at $200m$), at 06Z; (b) $900mb$ wet bulb potential temperature (shaded; interval $1K$) at 06Z and (c) $900mb$ wet bulb potential temperature at 12Z. In (a) and (b), a relatively weak anomaly of low level vorticity (marked 'W') is associated with a wave in the upper level PV height field, on the edge of the upper level trough. Other low level vorticity anomalies are marked 'A'. The θ_w wave can be seen to amplify between (b) and (c).

Figure 5: UKMO LAM analyses showing surface pressure ($4mb$ contours) and objectively analysed fronts (Hewson 1996; warm fronts are darker and $600mb$ fronts are dashed), for (a) 12Z on 14 November 1992 and (b) 12Z on 15 November 1992. The frontal wave becomes apparent as a spreading of the isobars on the warm front as it reaches the triple point at around 12Z on the 14th. Subsequently this secondary low deepened and by 12Z on the 15th, the primary had filled and moved towards the Bay of Biscay, as the two centres rotated around each other.

Figure 6: UKMO LAM analysis fields for 12Z on 16 February 1996, showing surface pressure ($4mb$ contours), objectively analysed θ_w fronts (darker shading for warm fronts; $600mb$ fronts are dashed) and $300mb$ jets ('tramlines'). The location of the secondary is indicated by 'W' and the approximate location of the 'triple point' by 'T'. At this time, the primary system lies just off the southern tip of Greenland and the secondary is developing on the trailing front, just off Newfoundland.

Figure 7: UKMO LAM analysis fields for 06Z on 17 February 1996. At this time, the primary lies at around 33W, 63N. (a) $900mb$ PV (shaded and fine contours, at $0.1PVU$ interval) with height of the $2PVU$ contour (heavy contours, $200m$ interval) superposed. The wave in the upper level trough is linked with the lower level PV anomaly, located at around 22W, 58N. (b) $900mb$ PV (contoured at $0.1PVU$) and $500mb$ PV (shaded at $0.1PVU$ intervals: lighter shading indicates higher values), showing the vertical structure of the secondary wave, to be distinct from that of the primary at mid- and lower levels.

Figure 8: UKMO LAM analysis fields, showing surface pressure ($4mb$ contours) and objectively analysed fronts for 17 February 1996 at times 00Z, 06Z, 12Z and 18Z. Warm fronts have darker shading. The secondary wave is marked 'W' and the 'triple point' is marked 'T'. Around 15Z the development at the triple point coincides with a rapid eastward propagation of the system.

Figure 9: The track of the primary low centre on 17 February 1996, as the minimum of local surface pressure. Surface pressure at 21Z is contoured, at $8mb$ intervals, and the low positions are labelled with their times of analysis. At 15Z a split in the low occurred, one pressure minimum remaining at the 12Z location and the new centre occurring to the southeast, representing rapid propagation.

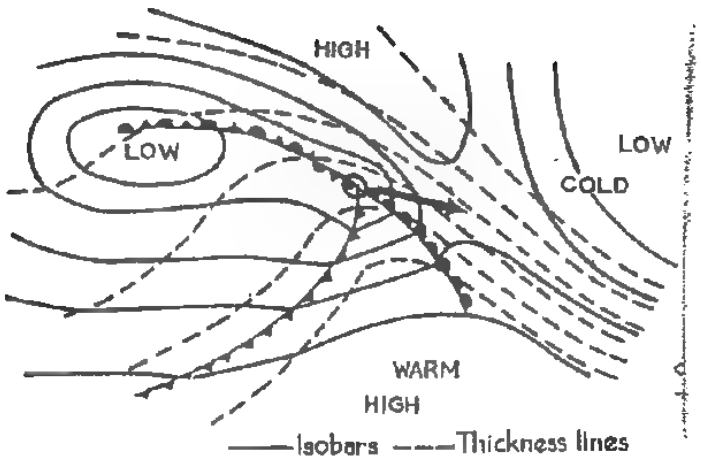
Figure 10: (a) A passive vortex strip (the edges of which are denoted by the bold lines) in a pure straining flow. In this flow, the strip will rotate towards the dilatation (frontogenetic) axis; (b) a sketch of the flow in the vicinity of the triple point of a frontal cyclone in which the warm front is undergoing frontogenetic strain.

Figure 11: The frontal cyclone lifecycle model of Shapiro and Keyser (1990): (I) incipient frontal cyclone; (II) frontal fracture; (III) bent back warm front and (IV) warm-core frontal seclusion. Upper: sea-level pressure, solid lines; fronts, bold lines and cloud signature shaded. Lower: temperature, solid lines; cold and warm air currents, solid and dashed arrows, respectively.

Figure 12: A cyclone approaching a blocking system from the west, along the 'frontolytic' axis of the large scale flow, from UKMO forecast analyses for 7 March 1996 at 00Z. Surface pressure is contoured (at $4mb$), and $1000 - 500mb$ thickness is in heavy, shaded contours. Shading is forecast precipitation and black lines are θ_w fronts; $600mb$ fronts are dashed. The upper level jet is denoted by the 'tramlines'. The synoptic-scale blocking pattern creates what appears to be the canonical pure strain flow: a front lies along the frontogenetic axis of this flow, trailing from the cyclone to the northwest. On the western 'frontolytic' axis of the flow, a cyclone is approaching.

Figure 1

(a)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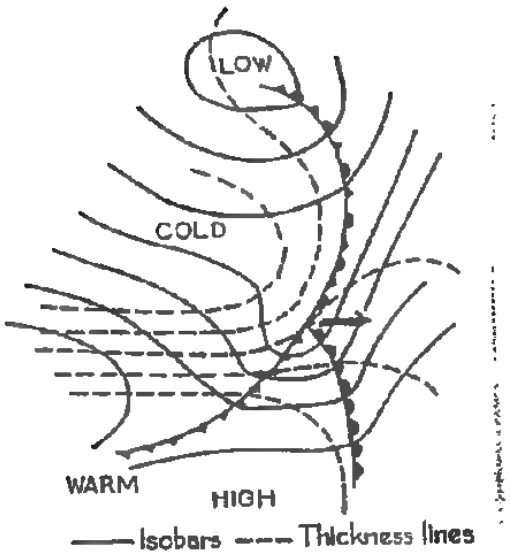
LOW
LOW
COLD
WARM
HIGH
——Isobars ----Thickness lines

(b)


LOW
COLD
WARM
HIGH
——Isobars ----Thickness lines

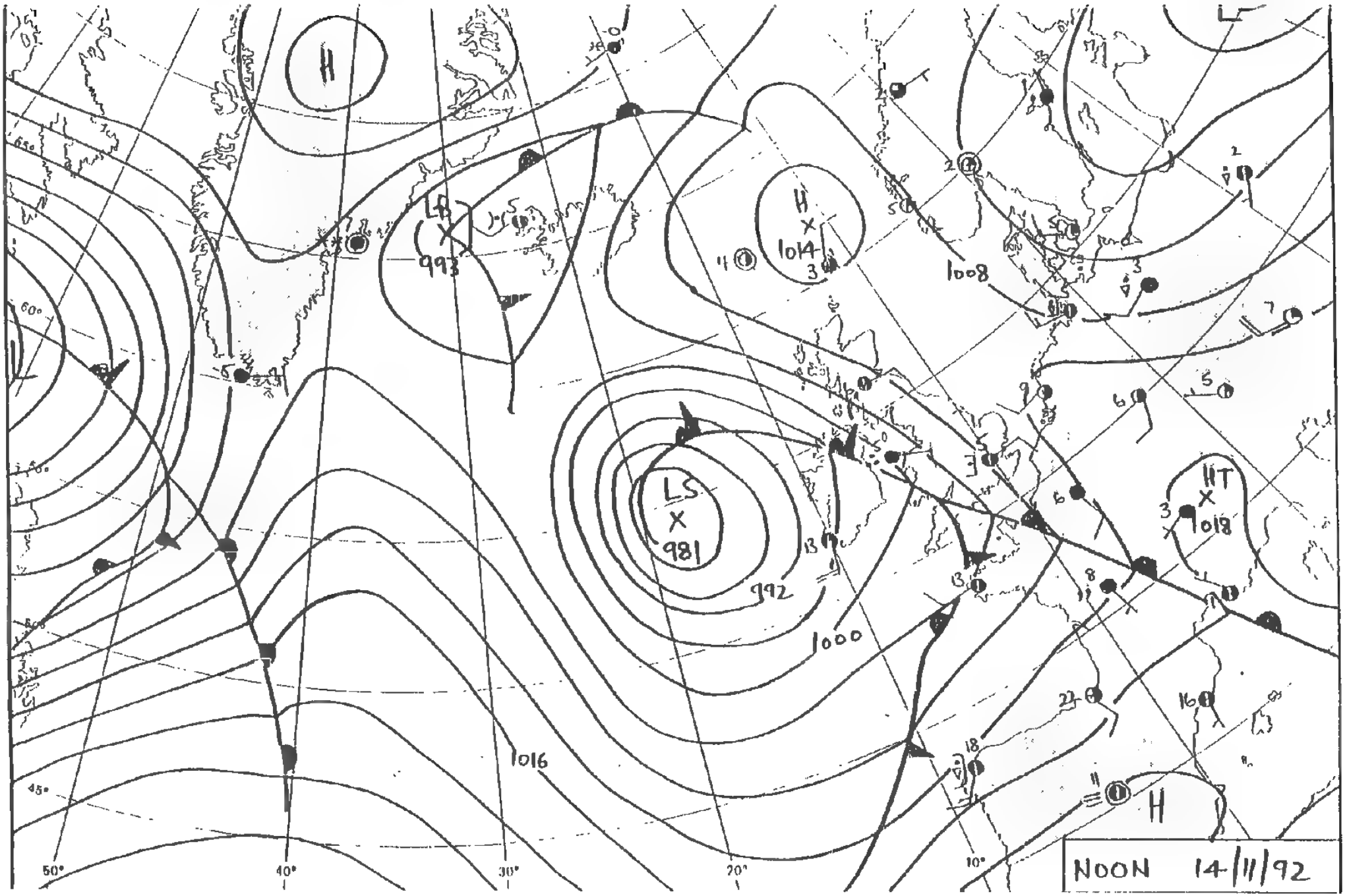
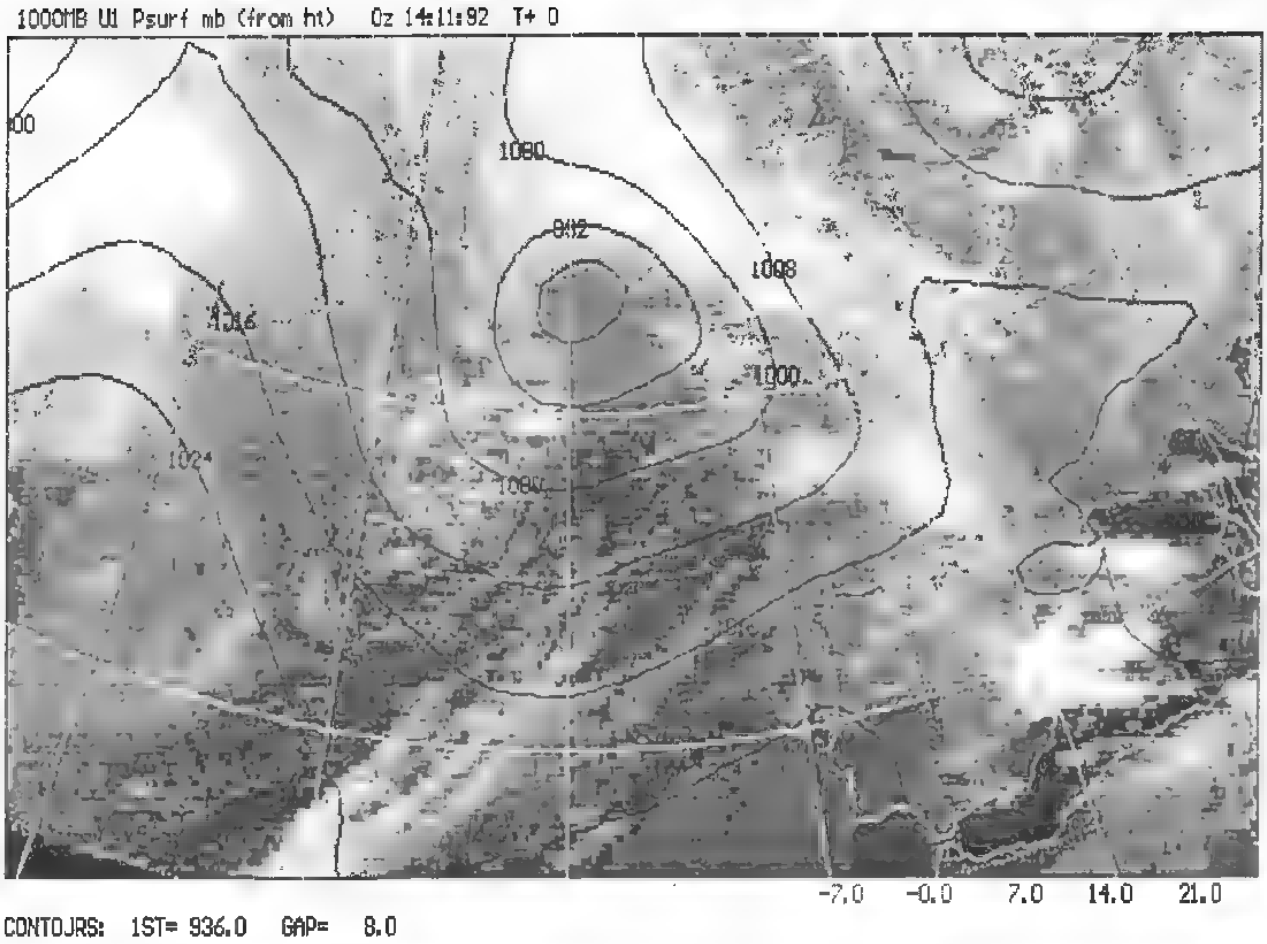

H
993
H
1014
1008
LS
981
992
1000
1016
HT
018
H
NOON 14/11/92
60°
50°
40°
30°
20°
10°

Figure 2.

Figure 3 007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1080
1012
1008
1016
1000
1024
1040
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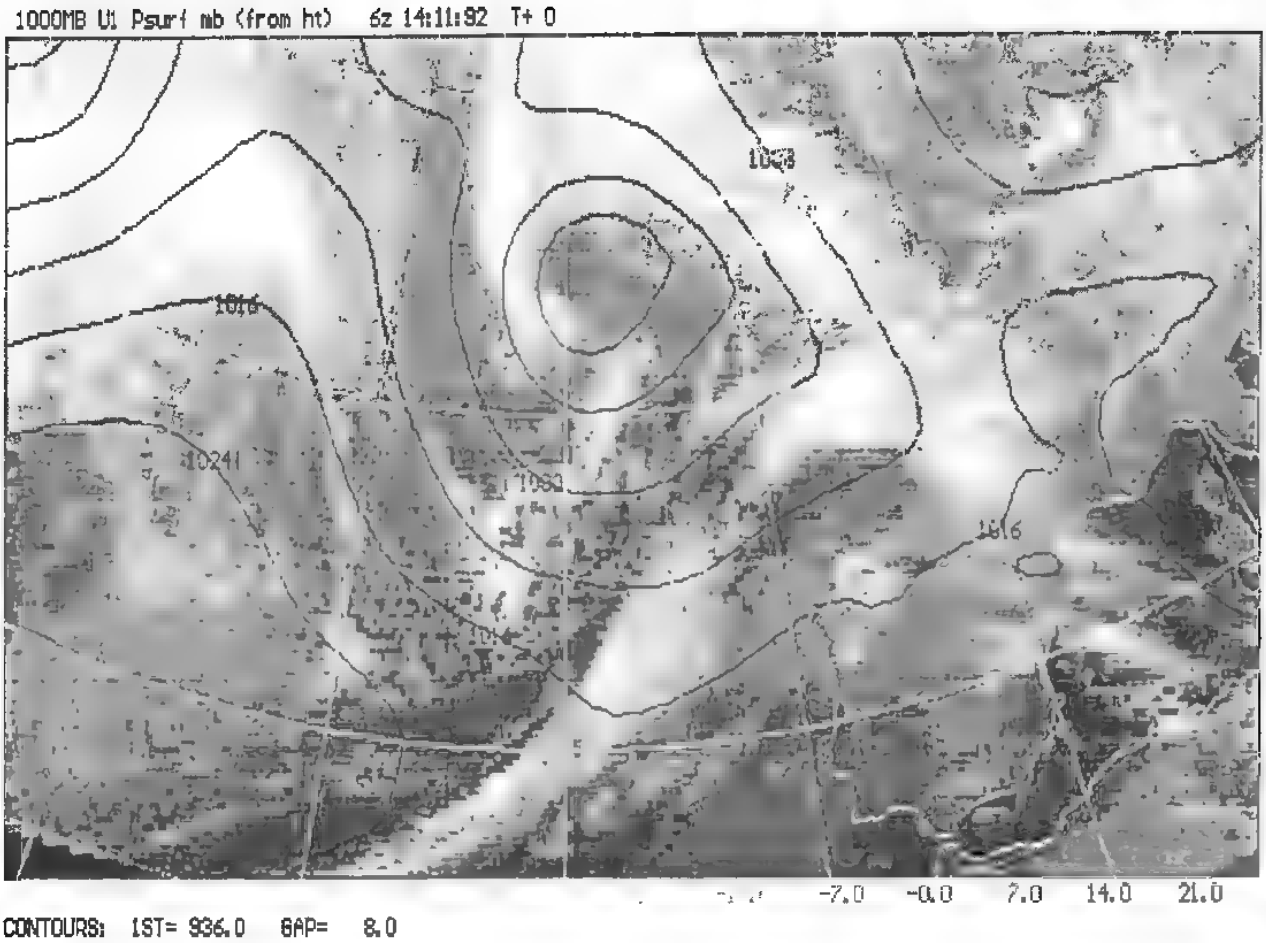
-0.0
7.0
14.0
21.0
CONTOURS: 1ST= 936.0 GAP= 8.0

Figure 3 067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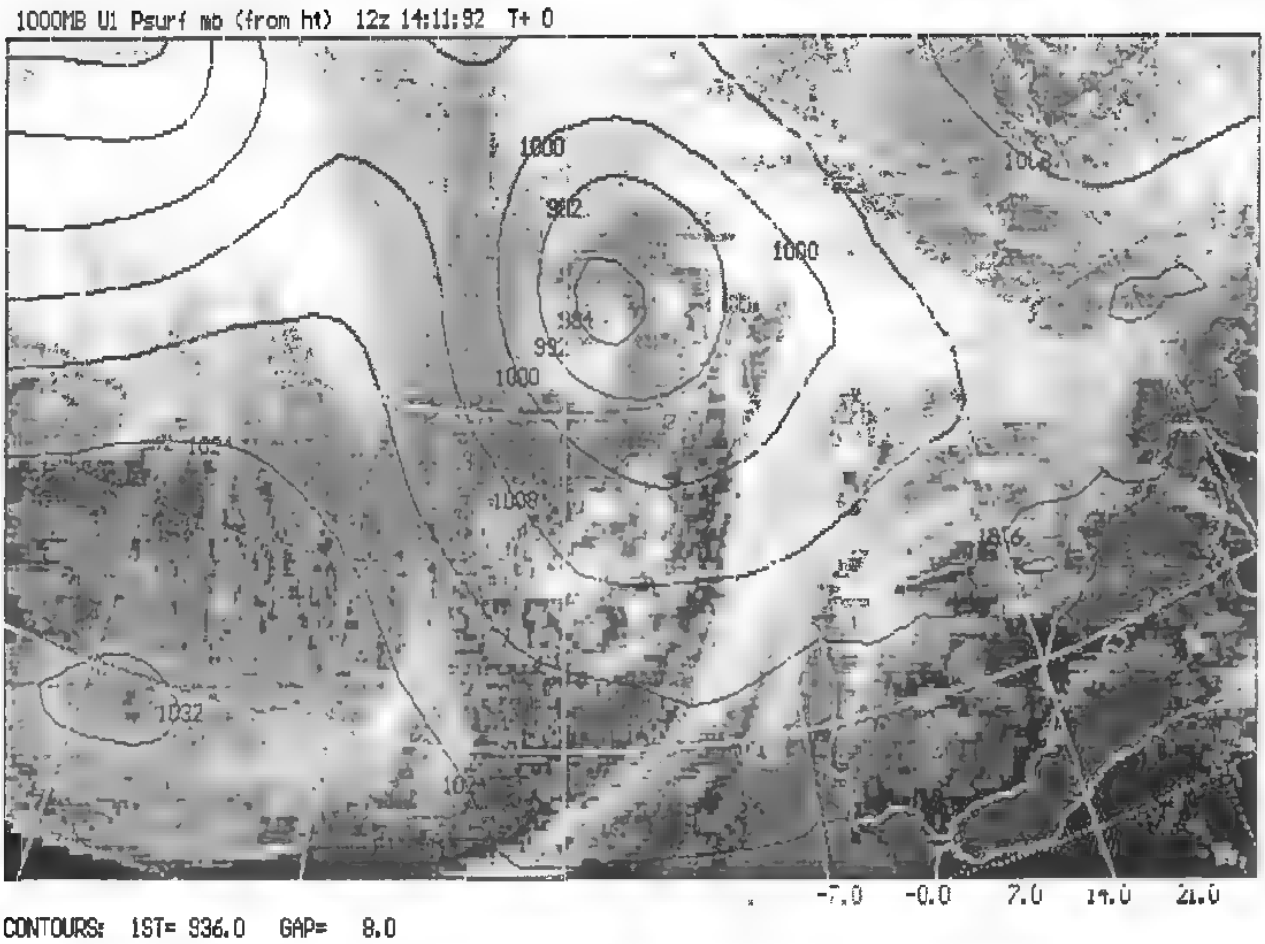
1043
1016
1024
1008
1016
-7.0
-0.0
7.0
14.0
21.0
CONTOURS: 1ST= 936.0 GAP= 8.0

Figure 3 127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1000
992
1000
1000
1032
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7.0
14.0
21.0
CONTOURS: 1ST= 936.0 GAP= 8.0

Figure 3 18Z

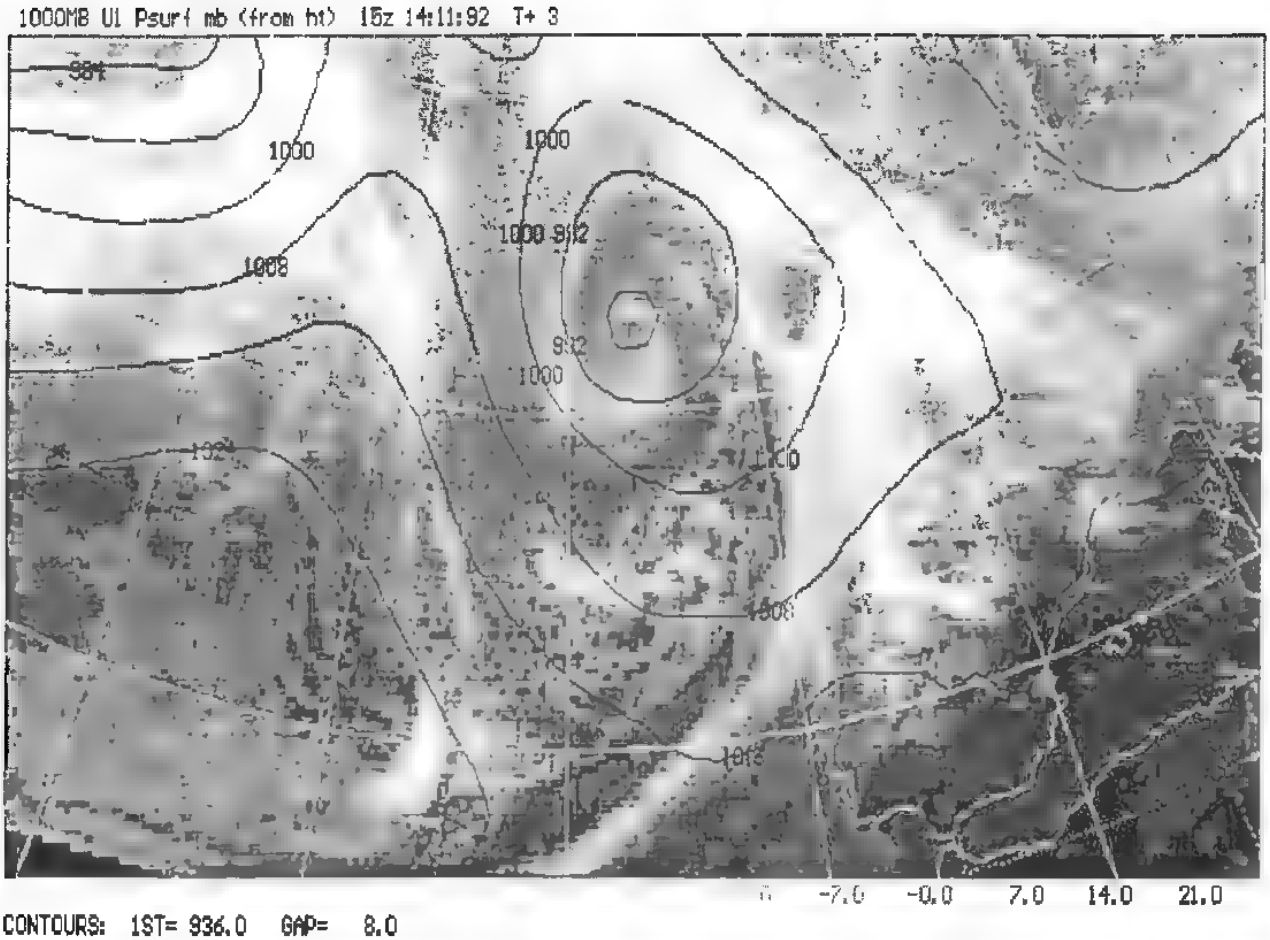

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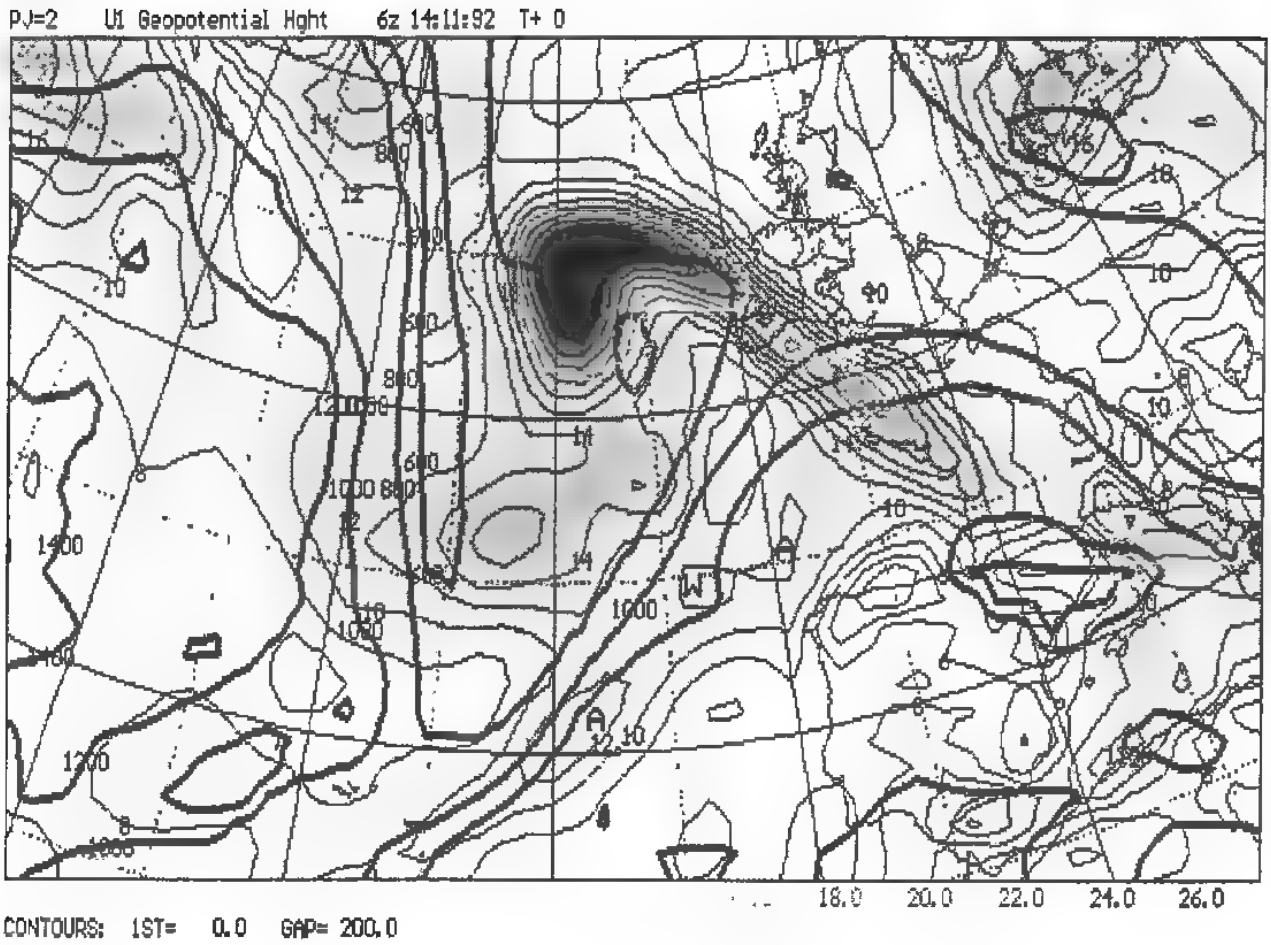
Figure 4 (a)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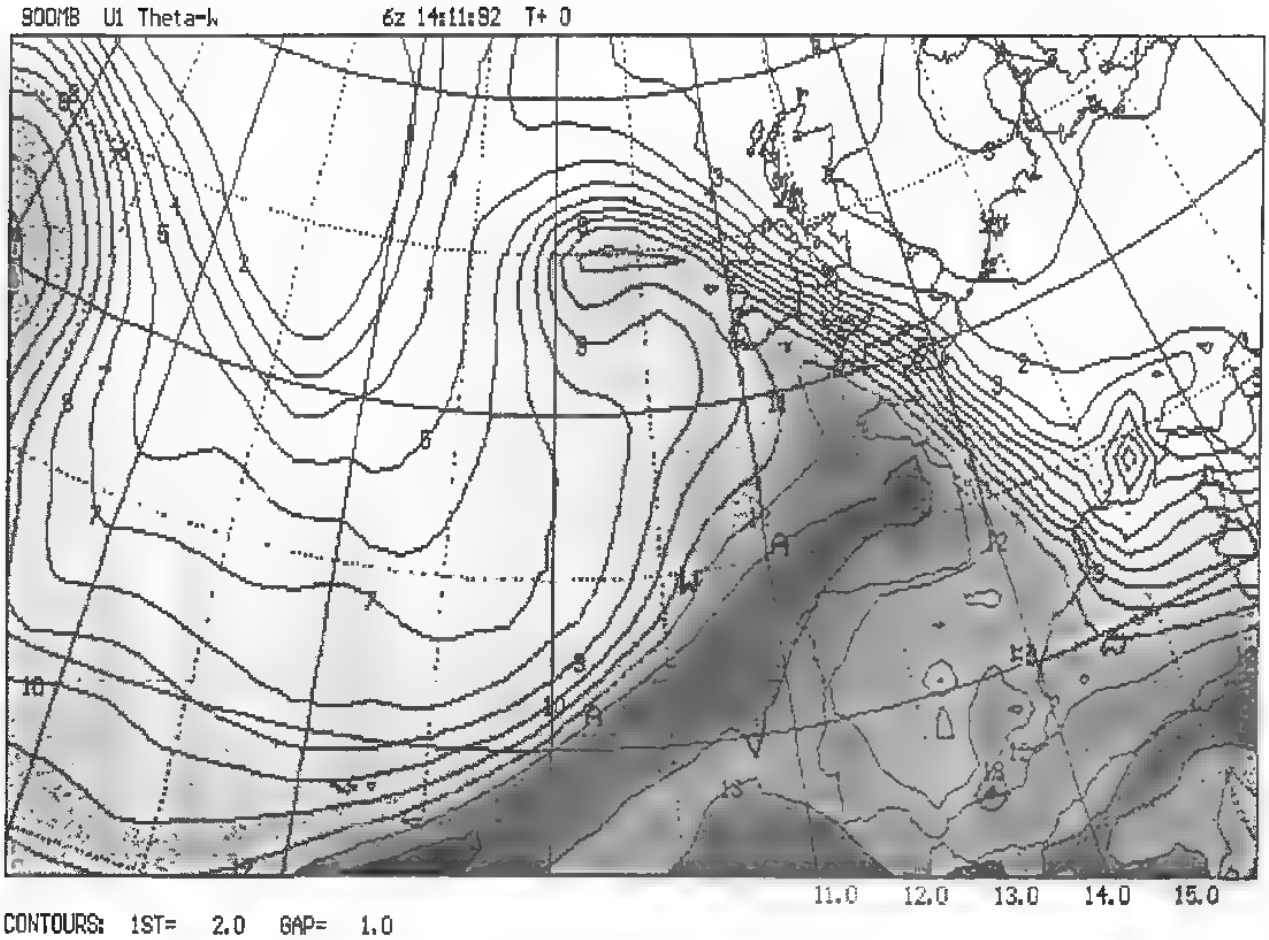
20.0
22.0
24.0
26.0
CONTOURS: 1ST= 0.0 GAP= 200.0

Figure 4 (G)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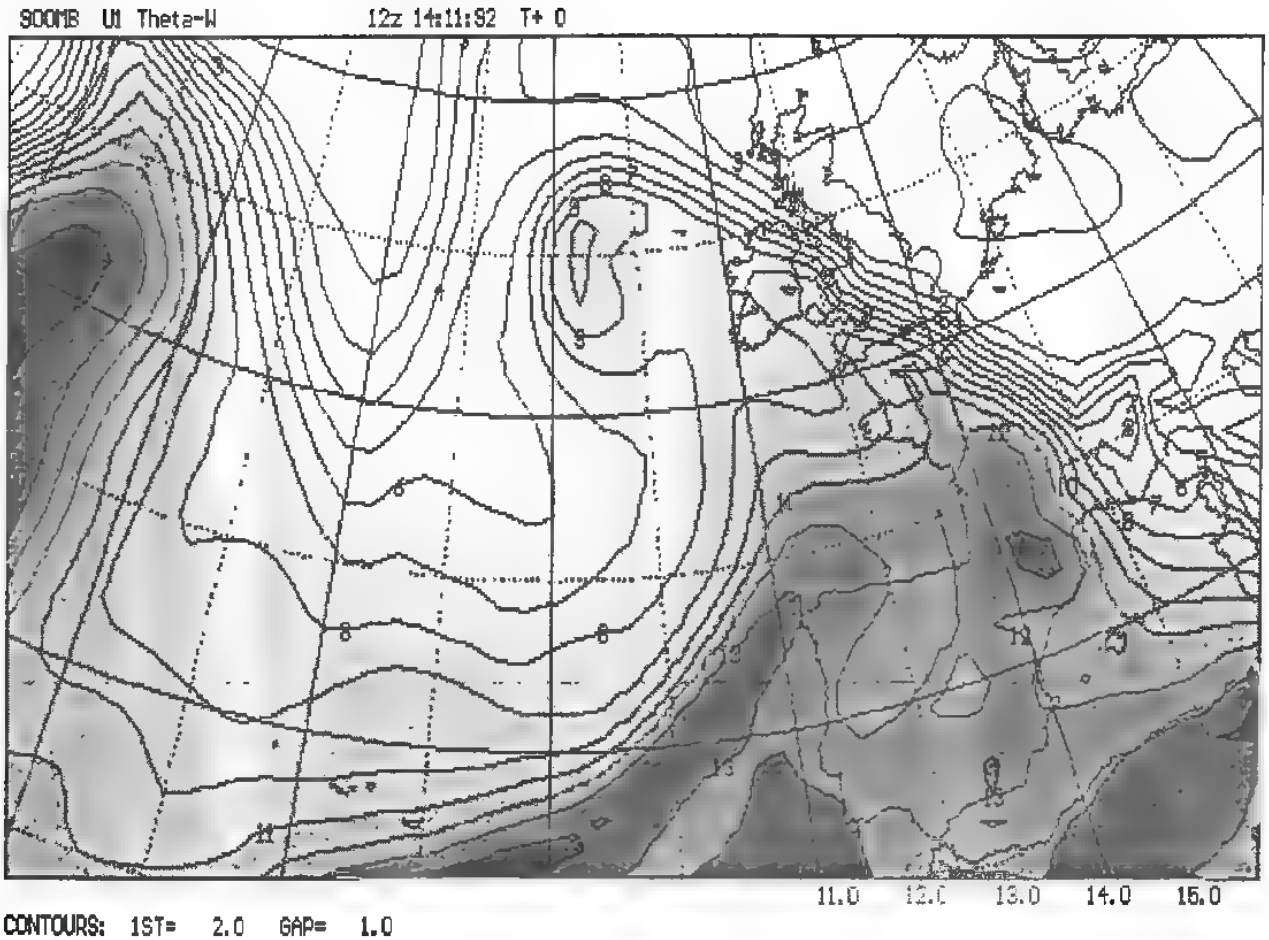
12.0
13.0
14.0
15.0
CONTOURS: 1ST= 2.0 GAP= 1.0

Figure 4(c)


SOOMB U1 Theta-W
12z 14:11:92 T+ 0
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12.0
13.0
14.0
15.0
CONTOURS: 1ST= 2.0 GAP= 1.0

Figure 5(a)

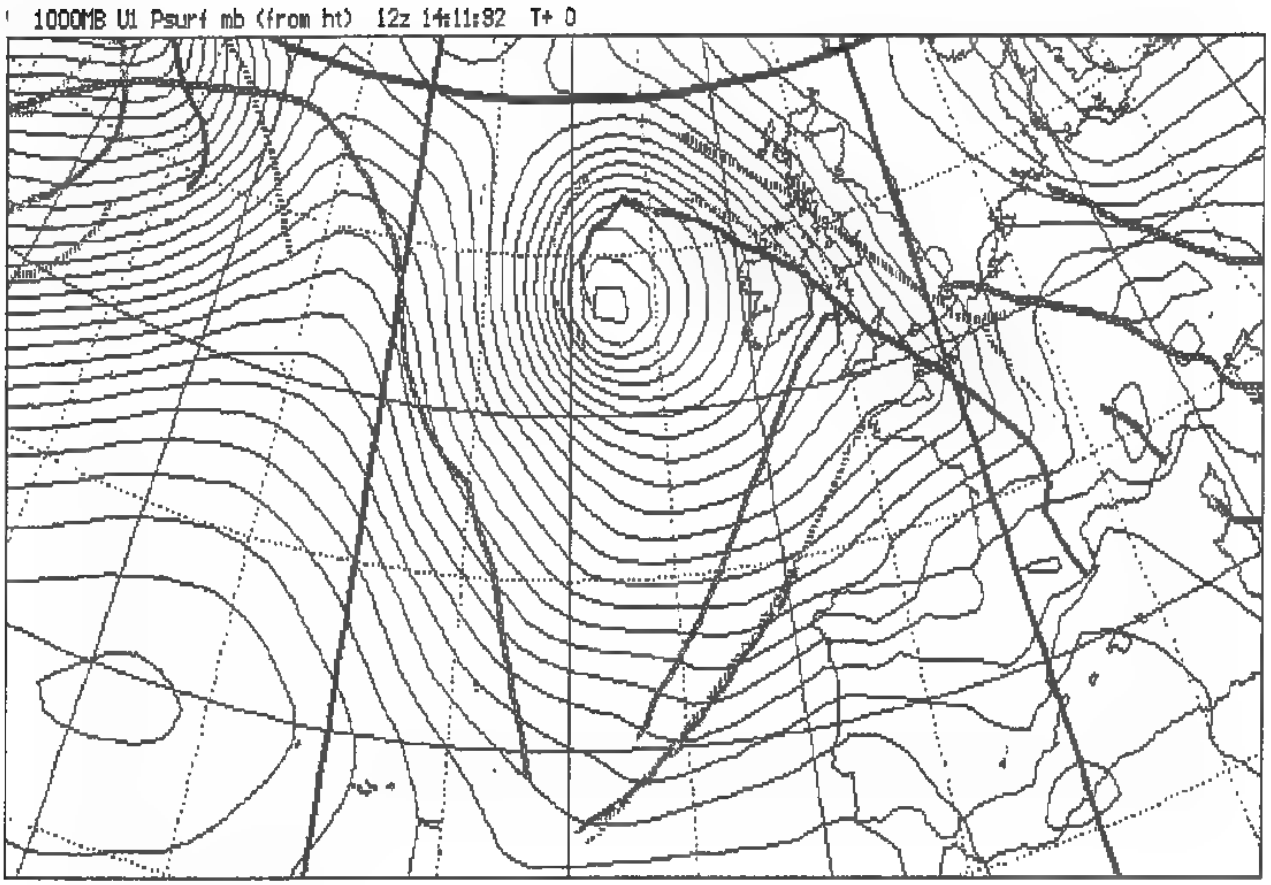
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Figure 5 (b)

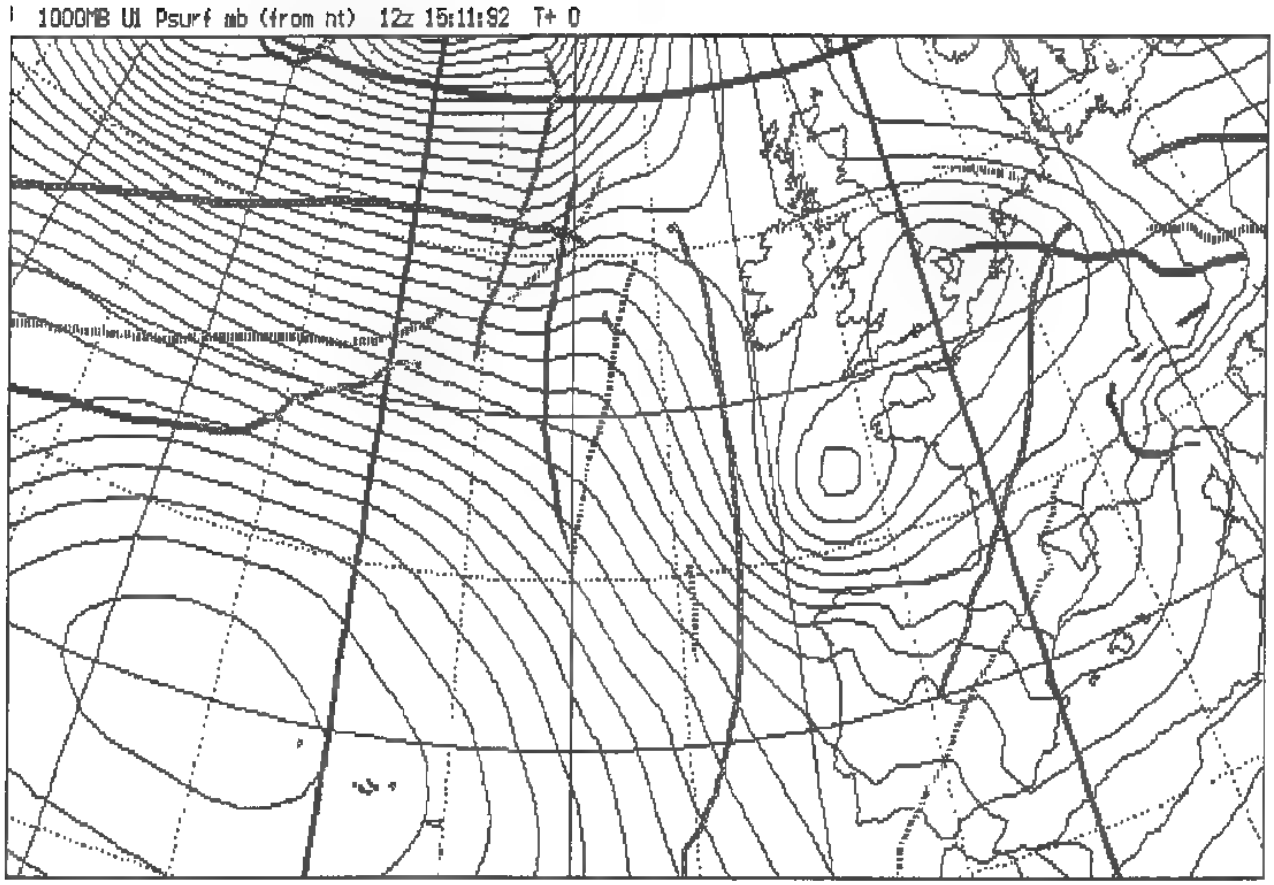
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Figure 6

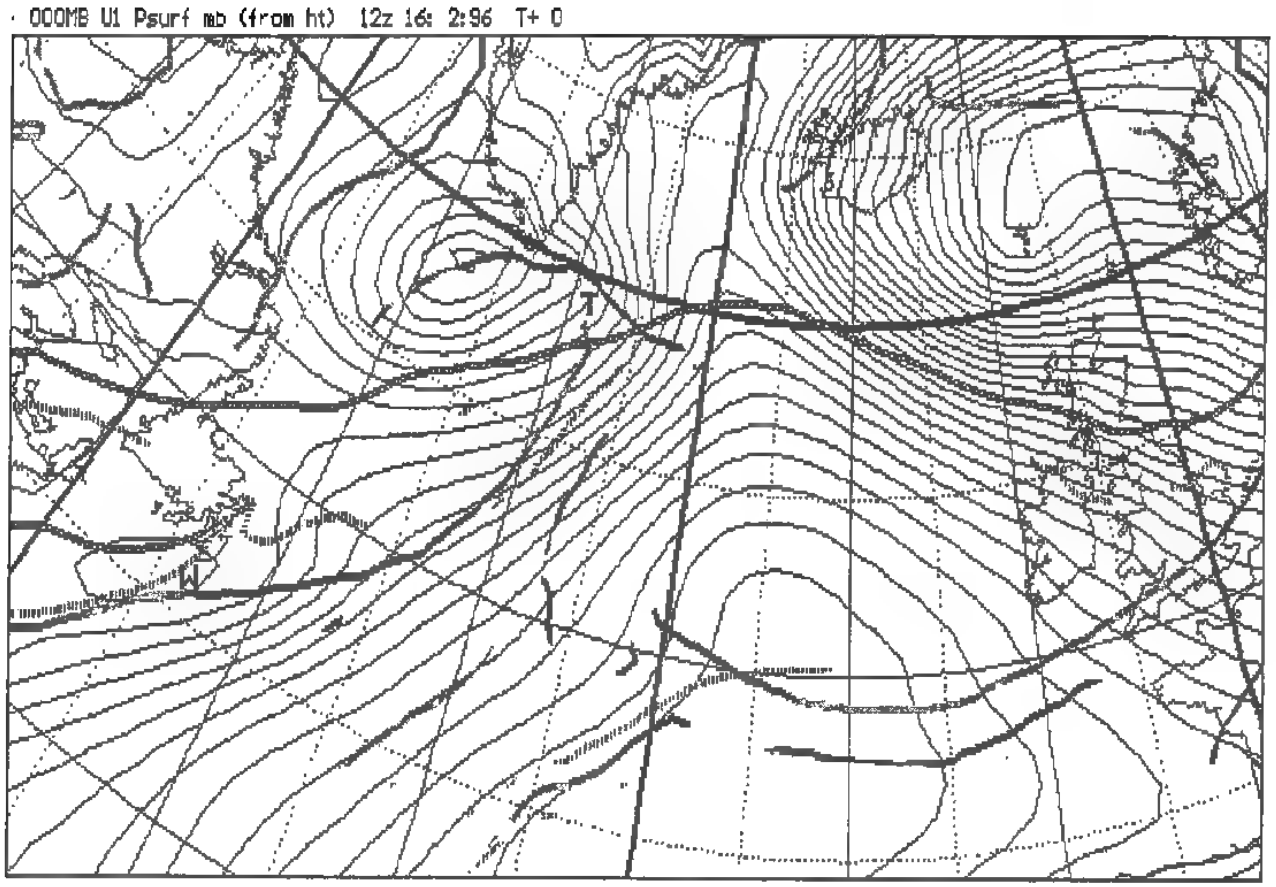
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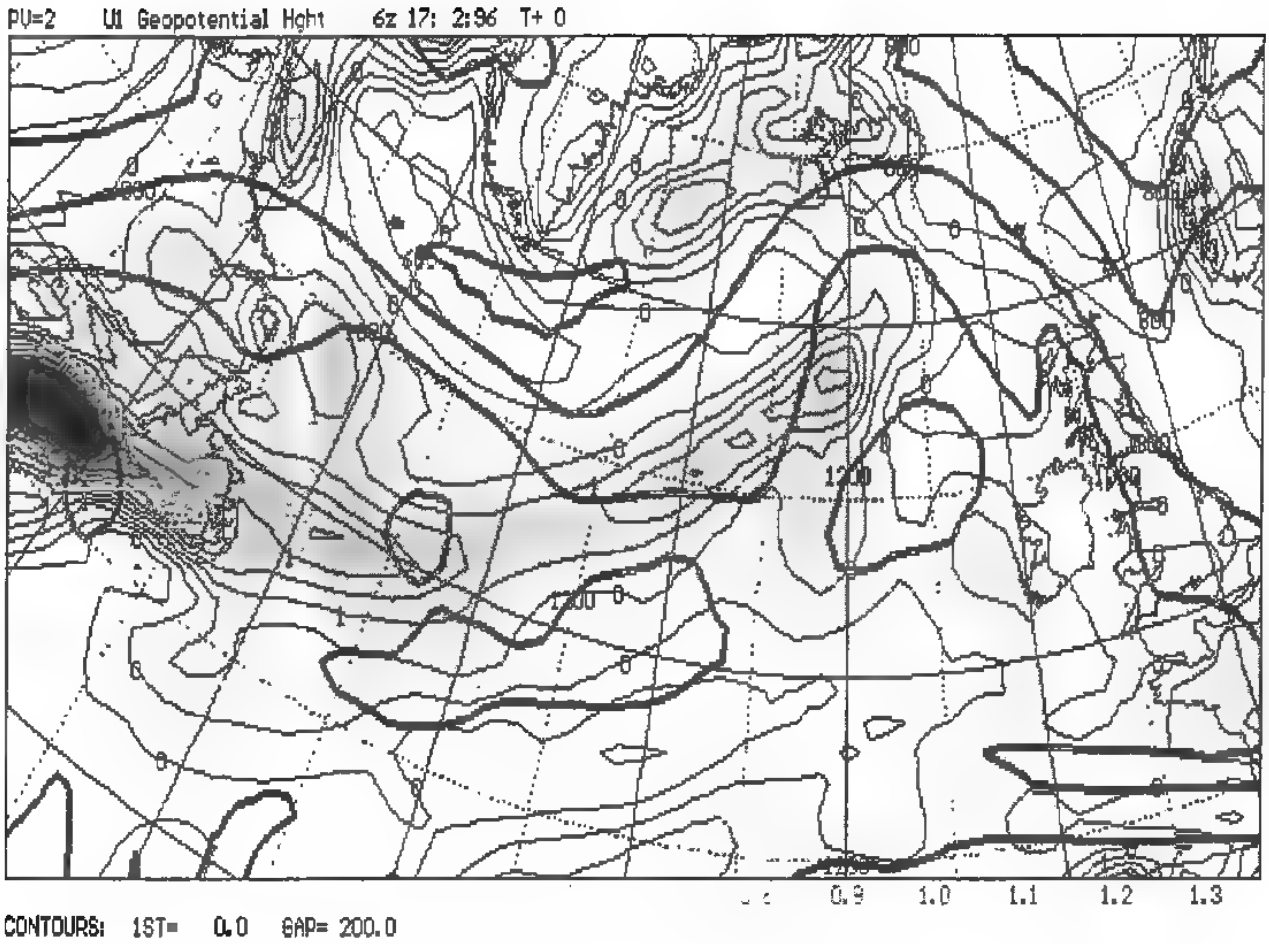
Figure 7 (a)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1.0
1.1
1.2
1.3
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Figure 7 (b)

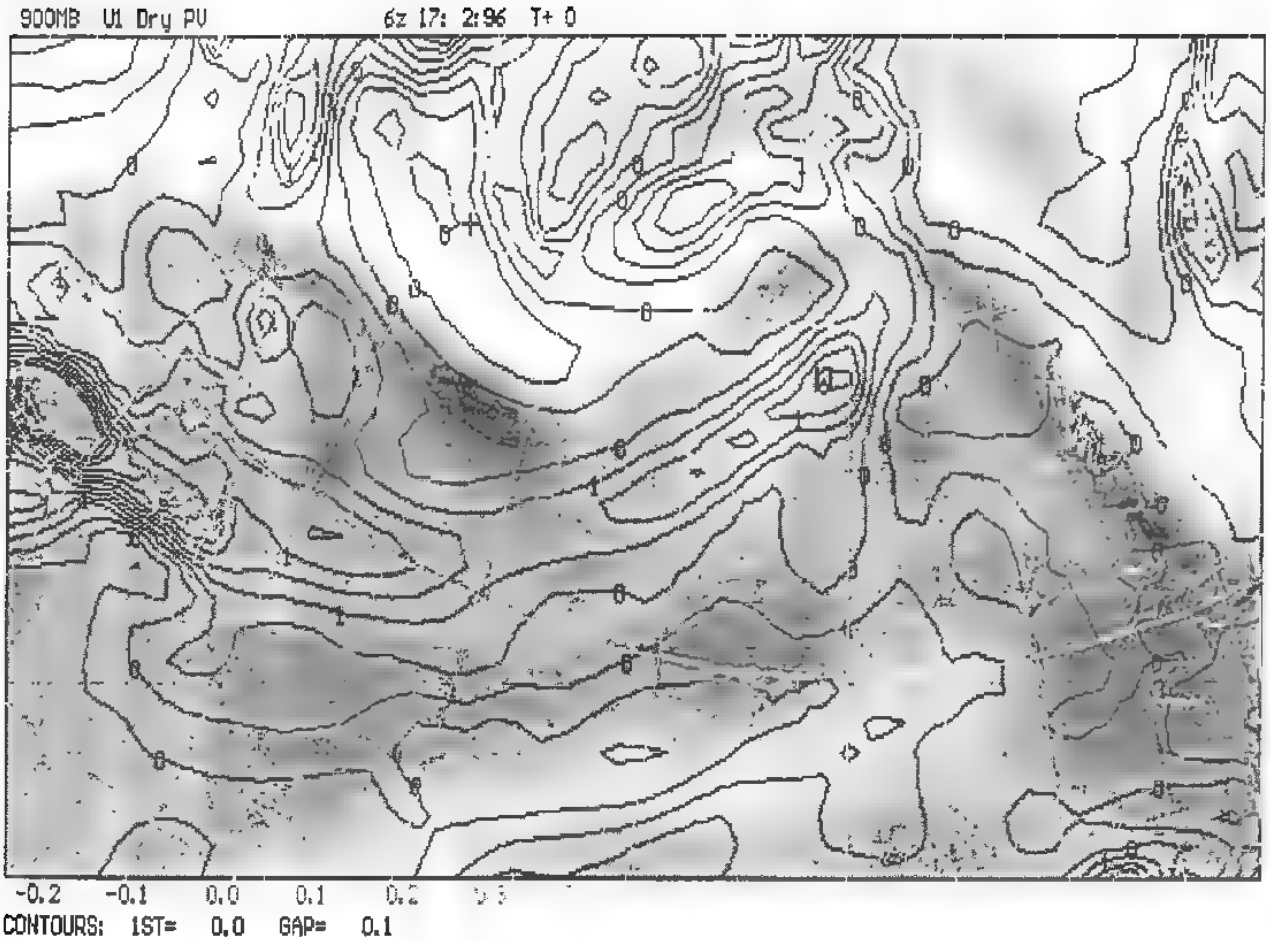
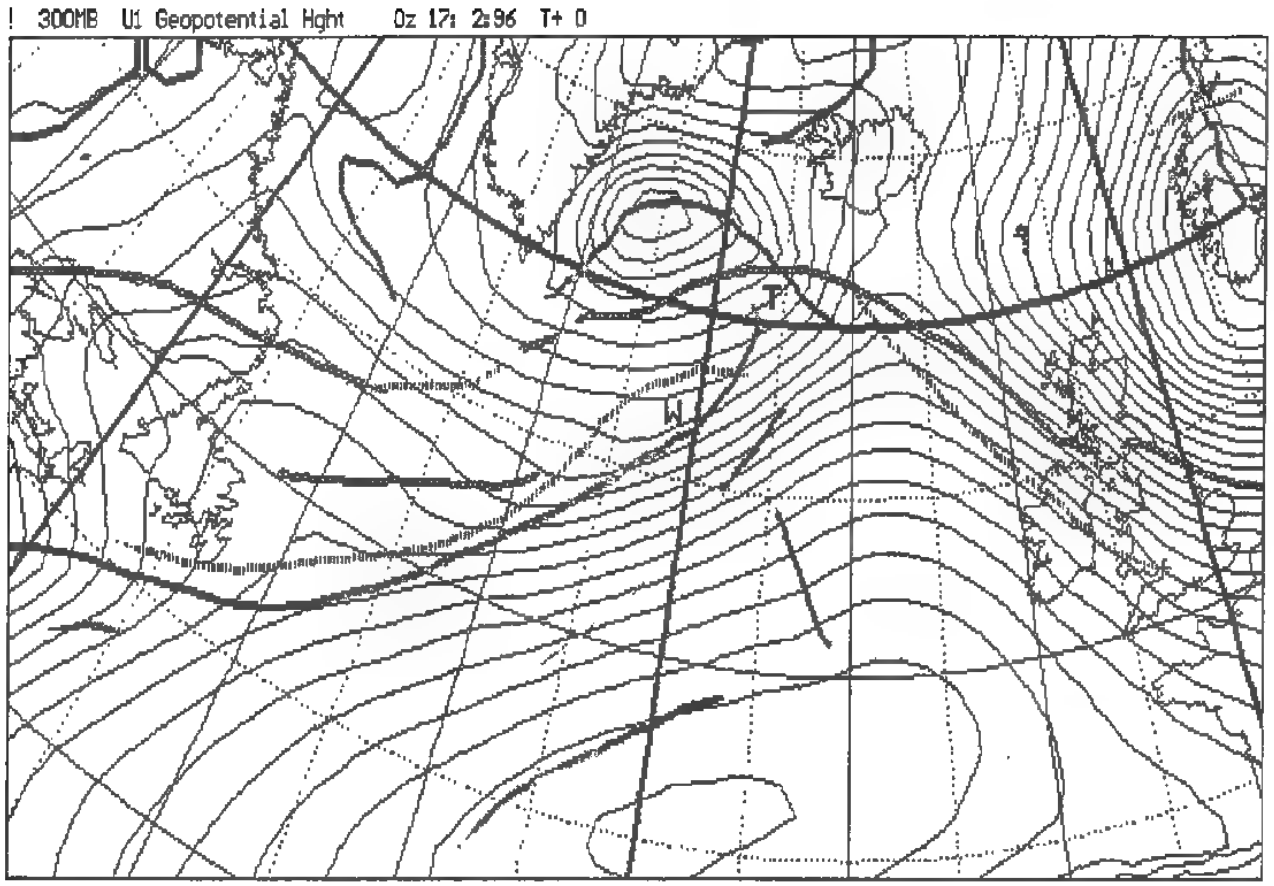


Figure 8 002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T
W
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Figure 8 062

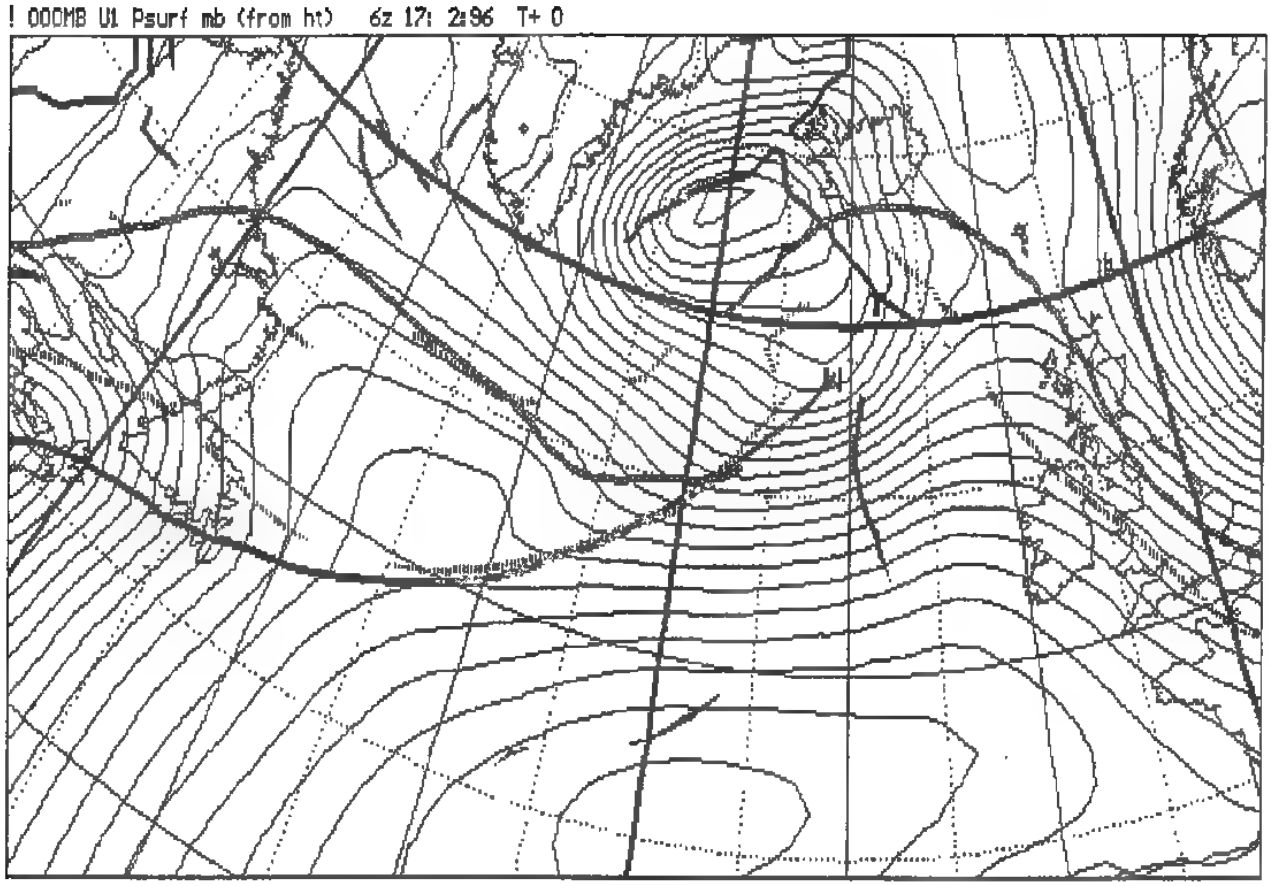
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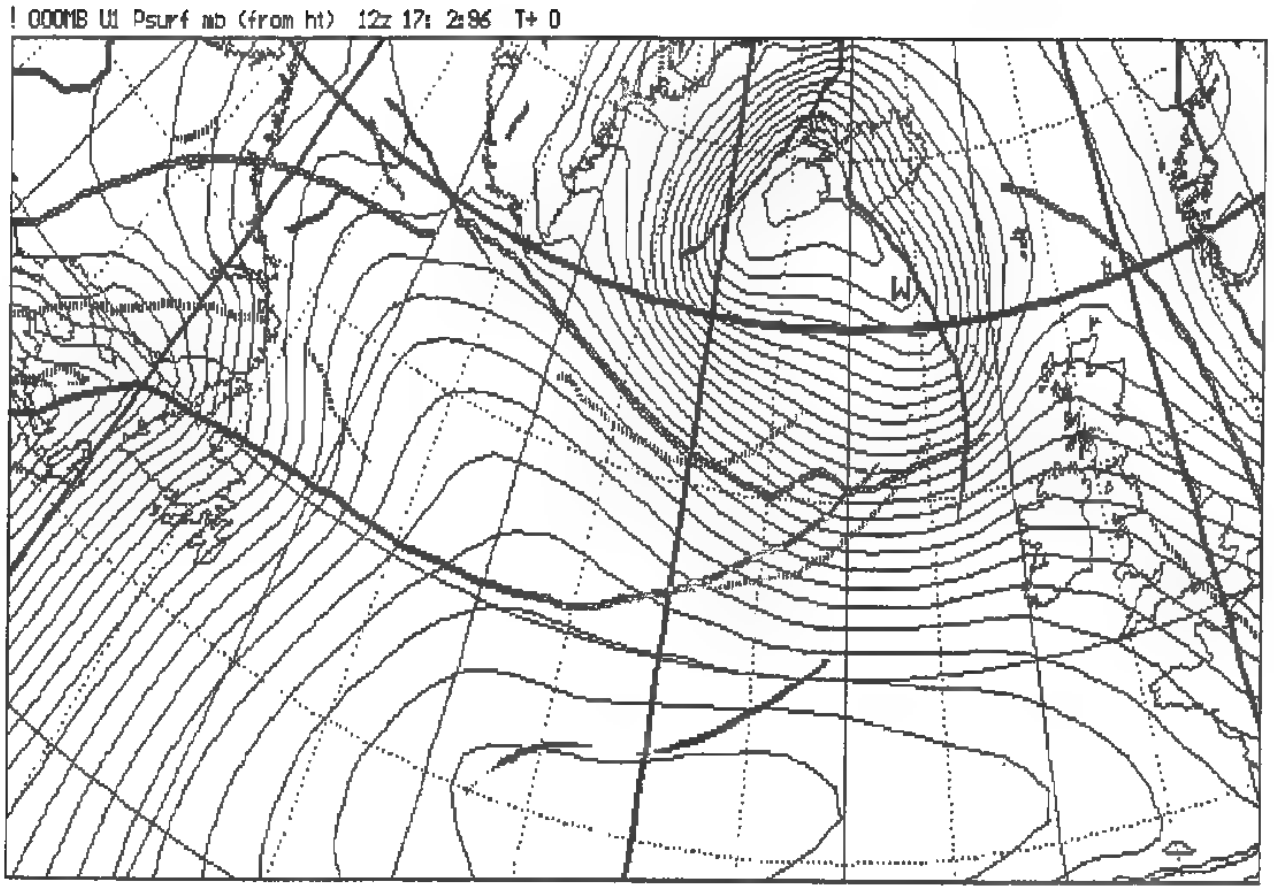
Figure 8 12Z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W
CONTOURS: 1ST= 936.0 GAP=n/a2.0

Figure 8 182

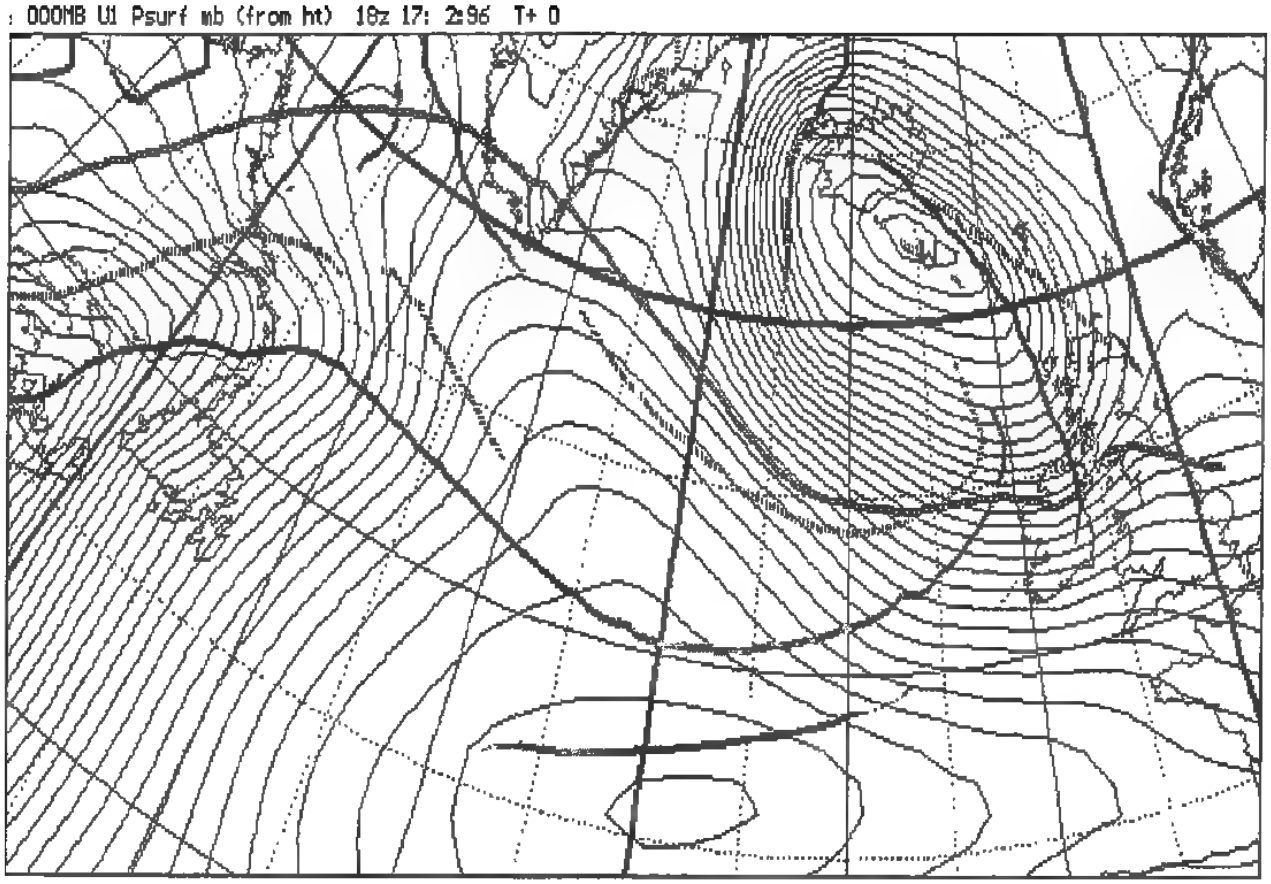
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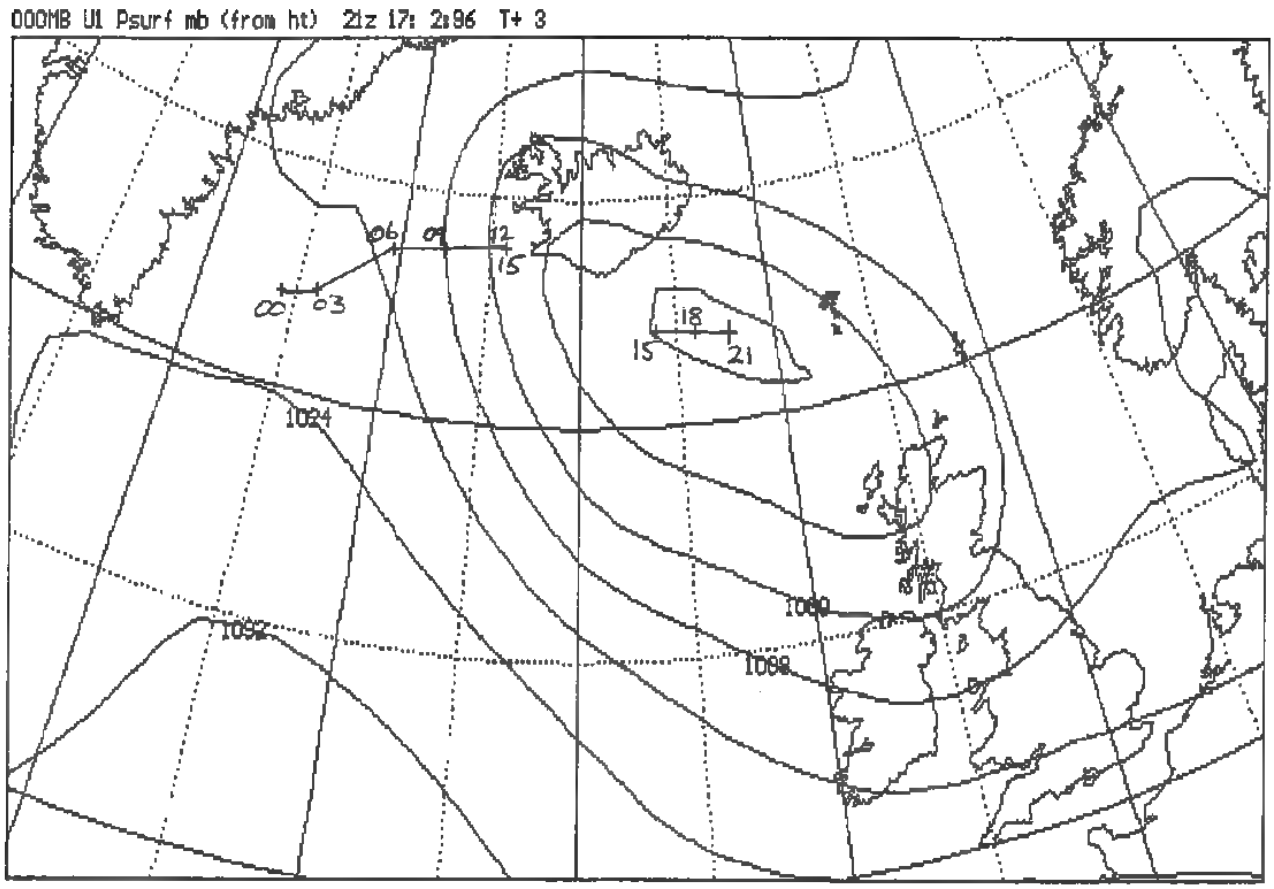
Figure 9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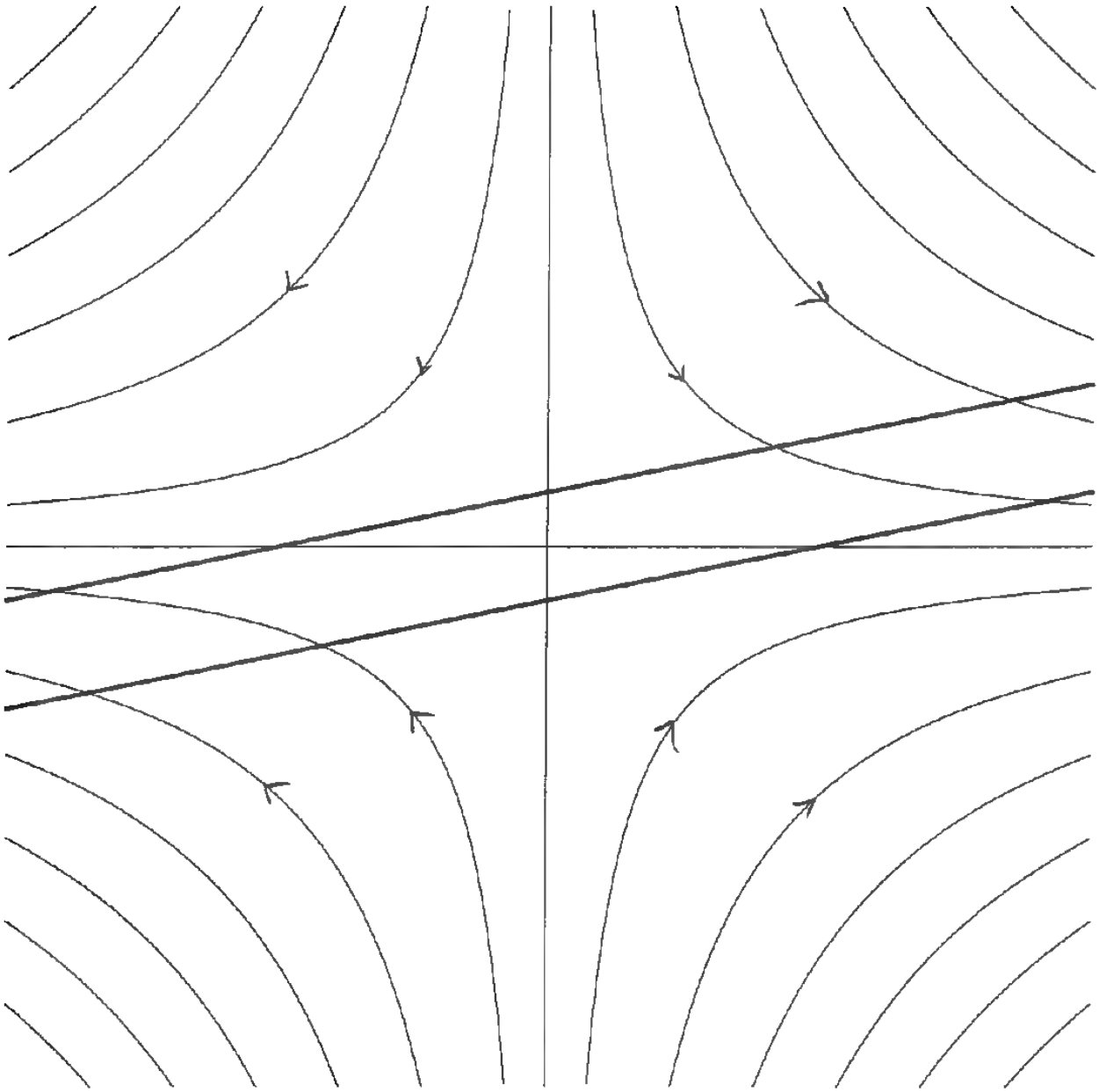
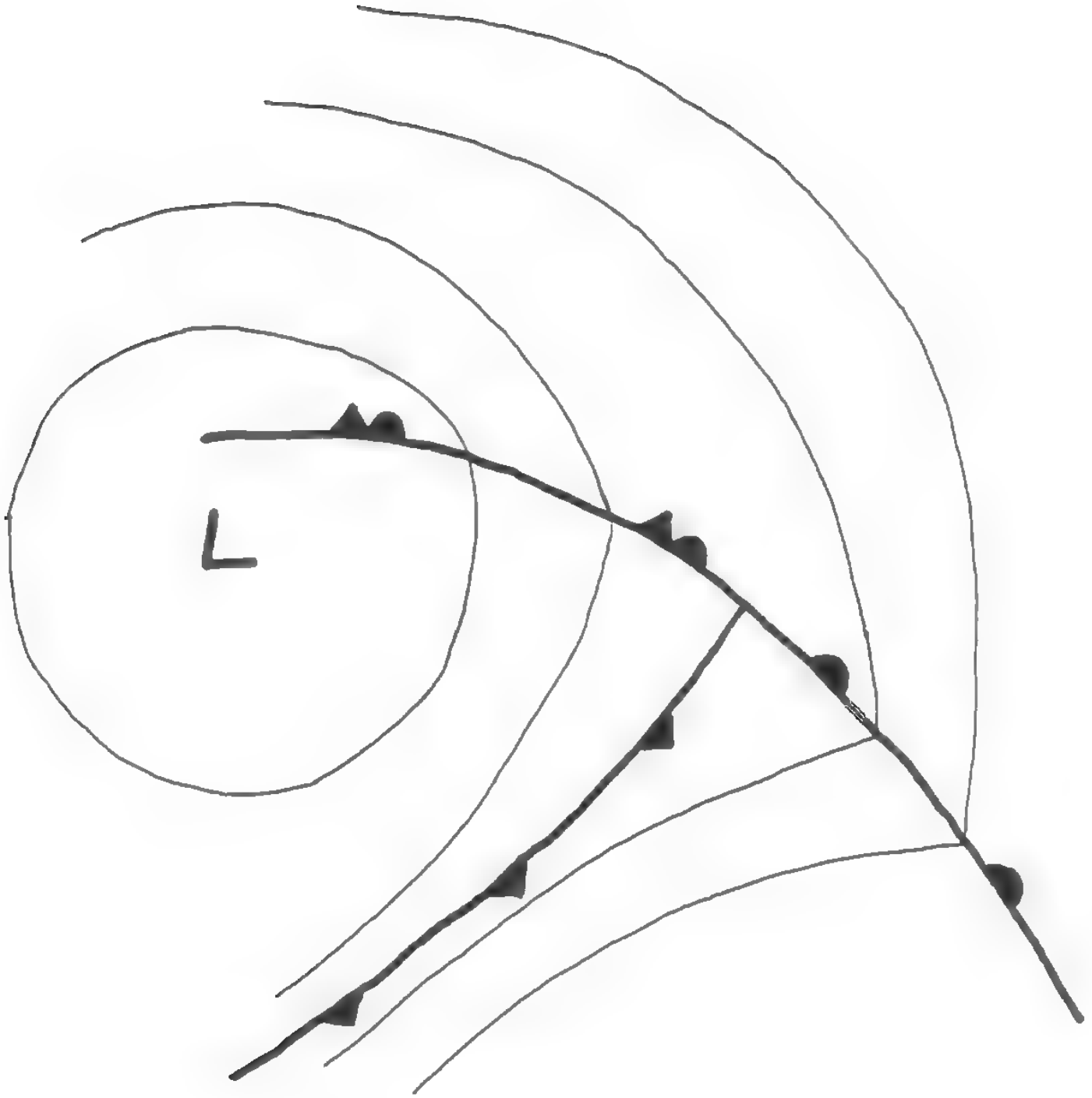
06
09
12
15
00
03
18
15
21
1024
1092
1088
X= 1920.2 Y= 1320.8 981.9

Figure 10 (a)





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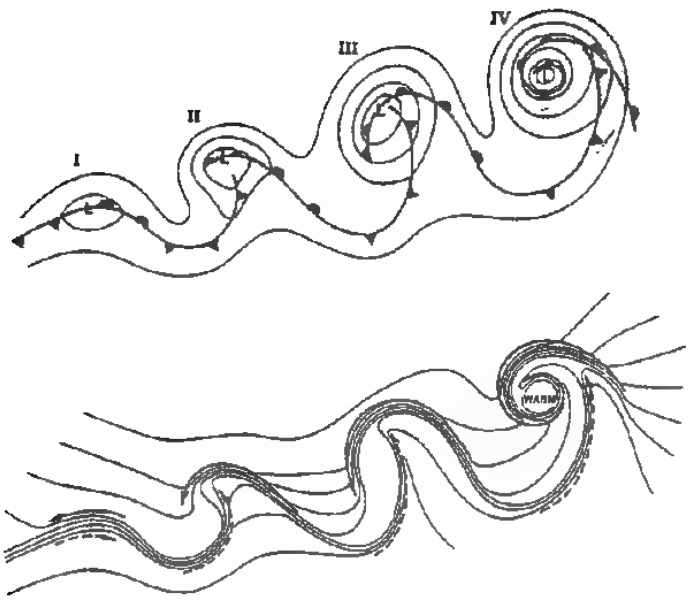
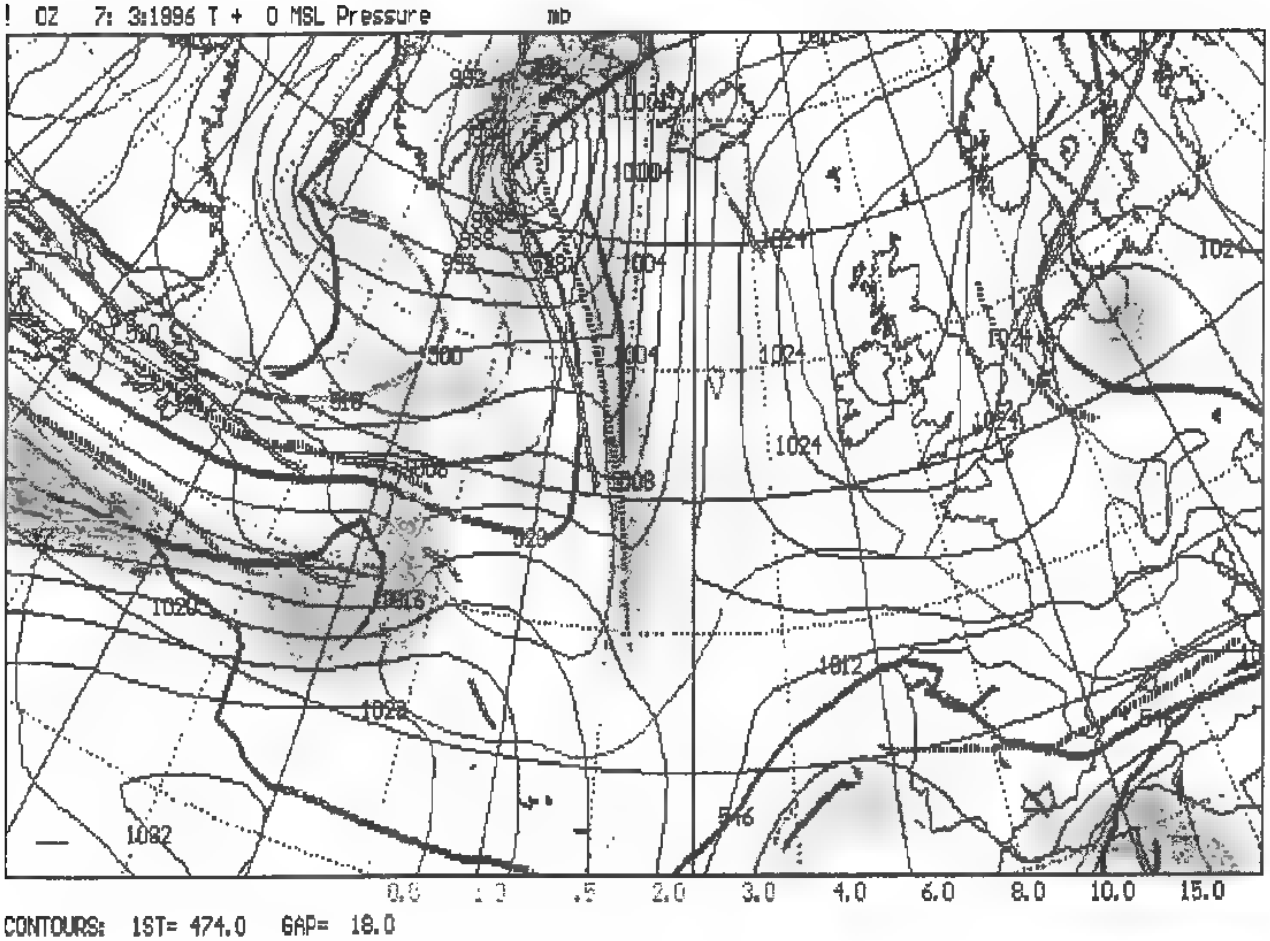


Figure 11

Figure 12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1012
1020
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.5
2.0
3.0
4.0
6.0
8.0
10.0
15.0
CONTOURS: 1ST= 474.0 GAP= 18.0

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